Why does the river erosion situation become more complicated in the Mekong delta?

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Abstract:

Being a young river located in the delta that has been forming for a few thousand years now and developing during the several hundred years in the recent past under the pressure of socio-economic development, the impact of climate changes, rise in the sea level, and the Mekong upstream development, the riverbeds and coasts in the Mekong delta have currently transformed the erosion from an acceptable "chronic" and "essential" situation to a complicated, unpredictable, and alarming one. This is the cause behind the serious damages to local people and the infrastructures along the river banks and coastlines.

Understanding the basic causes, recognizing the continuous trends, or proposing the effective and feasible response solutions are the most important problems for the local people and the authorities, those of the Central Government and the those in the localities. Therefore, we must prepare for river banks' or coastlines' and valuable materials' or entities' protection, plan and stabilize the populated areas along the river banks and coasts, especially in the high-risk erosion areas. These are the major contents that would be presented as follow.

Keywords: ***erosion, Mekong delta, sediment.***

Classification number: ***6.2***

Rivers and coastlines are considered to be living organisms. The living organisms always move. One of those movements results in siltation and erosion, generally known as the river metamorphosis. In addition, for living organisms, the metamorphosis is intermittent, rapid or slow, and strong or weak, from both the inside and outside elements. In the scope of this research, we would discuss the river bed and the coastal erosion sequences during the recent years in the Mekong delta.

Some major natural principles of river sequences in the Mekong delta

The Mekong delta river bed sequence principles by time and space are very diversified and complicated. The following are some of the typical principles:

Divided/incorporated rivers: right after entering the delta, both the Mekong and Bassac rivers start the division/incorporation process by forming a series of consecutive divided/incorporated nodes and end in all the distributaries that flow into the sea. The phenomenon of river shortcuts might have occurred several times in the past, on the segment from Phnom Penh to the Vietnam-Cambodia border and in the dead river segments that had formed in the current natural swamps and lakes (such as Bung Binh Thien and An Giang province). With tens of instances of river division and incorporation, the Mekong river might be laid on a less stable geological foundation. After many consecutive divided or incorporated nodes, from the Vinh Long province, the river starts its division process to constitute four separate distributaries flowing directly into the sea, namely, Cua Dai, Ba Lai, Ham Luong, and Co Chien. This process also happens at two other distributaries to separate the Cua Dai into Cua Dai and Cua Tieu, and the Co Chien into Co Chien and Cung Hau river mouths.

Located on the quite stable geological foundation and flowing parallel to the Mesozoic folds in the deep layer, the phenomenon of division/incorporation is fewer in the Bassac river. While approaching the sea, the river also splits into two mouths (formerly, the Bassac river had three mouths, but the middle one, namely, Bat That, the last in the nine mouths, disappeared about 100 years ago by sedimentation). Generally speaking, the continuous division/incorporation and formation of the distributaries when approaching the sea are the typical characteristics of the Mekong river system. This phenomenon can be assembled from various reasons, such as a sudden increase or decrease in the water flow velocity in the alternate wide or narrow river segments, which bring material sedimentation and form the alluvial grounds (in the middle of the Mekong and Bassac segments), or due to the non-coincidental dynamic axis of the flood/low-flow seasons, creating the slack velocity zones and the gradual sedimentation (in the upper Mekong and Bassac segments). In the strongly tide-affected zones, the river division process is formed by many combined elements. There exists a close relationship between the sediment/flow distribution and the cross-sectional area of each distributary. This allows us to explain the phenomenon of sedimentation on

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some branches along the river, such as the downstream of the Vam Nao distributary, Cao Lanh or the Cai Be creek (Sa Dec) on the Mekong river (Table 1, Fig. 1).

Table 1. Characteristics of morphology for the Mekong and Bassac rivers.

River segment	Distance from the estuary (km)	River	Cross sectional area (m^2)	Mean width of segment (m)	Mean depth of segment (m)	Hydraulic radius (m)
Estuary	0-60	Mekong	5,795	853	-10.0	6.87
		Bassac	17,870	1,860	-12.5	9.84
Middle	60-140	Mekong	6,722	882	-17.3	8.45
		Bassac	10,552	962	-16.6	11.20
Upper	140-220	Mekong	8,207	853	-15.5	10.30

(Sources: The data are summarized from [1] and a lot of other sources and at different moments).

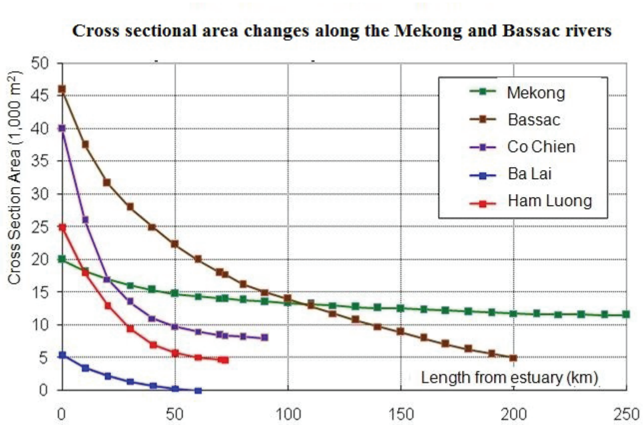

Fig. 1. The changes in the cross-sectional area along the Mekong and Bassac rivers (Sources: The data are summarized from [1] and a lot of sources and at different moments).

The formation of curved river segments: an important feature of the river flow and river bed mechanism is the formation of the curved river segments, of which, the most prominent is in the Mekong river. The curved form is ever better than straight to balance the kinetic energy between the flow and the bed. Consequently, the curved is the most sustainable form of rivers located in the land, which are easily eroded in the Mekong delta. Some typically curved segments are at Tan Chau, Sa Dec, and My Thuan on the Mekong river, and Khanh An (near the border), Vinh Thanh, and Long Xuyen on the Bassac river. However, due to the unformed balance state, some curved segments on the Mekong river are still strongly being dug and eroded. Meanwhile, some other river segments, most of which are on the Bassac river, have progressively advanced to the necessary stable state. The transformation of the curved segments is often associated with the process of thalweg shifting, especially on the riverbeds. These thalwegs squeeze on the concave banks and increase the erosion ability, mainly in the flood season, to form the abysms close to the river banks, such as the abysms at Tan Chau, Hong Ngu, Sa Dec, and Vinh Long on the Mekong river (Table 2).

Table 2. The characteristics of the curved segments on the Mekong and Bassac rivers.

Curved segment	W_{max}, (m)	W_{min}, (m)	R, (m)	L, (m)	L', (m)	K, (L/L')	Z_{min}, (m)	Z_{mean}, (m)
Mekong river								
Tan Chau	1,850	600	26.0	15,000	11,600	1.29	-45.1	-20.0
Sa Dec	1,500	800	15.5	24,000	21,600	1.11	-28.5	-10.3
Vinh Long	1,000	440	19.9	3,900	3,650	1.07	-35.0	-14.7
Bassac river								
Chau Doc	1,100	270	15.5	13,000	9,000	1.44	-25.8	-13.0
Chau Thanh	1,200	580	18.4	14,000	13,000	1.08	-21.0	-17.5

Notes: W_{max}: maximum width; W_{min}: minimum width; R: hydraulic radius; L: length of curved segments; L′: length of the curved segment by straight; K: curved coefficient; Z_{min}: most depth; Z_{mean}: mean depth.
(Source: the data are summarized from [1] and a lot of other sources and at different moments).

The formation of alluvial grounds and islands: alluvial ground formation is associated with the river division/incorporation process, with the flow movement being ruled by the seasons and along the rivers, with the composition and size of suspended and bottomset bed materials carried by flows. At the same time, alluvial grounds have the opposite effect on the flows, such as by increasing the velocity before and after the division of the distributaries to form the eroded pits, causing the alluvial grounds to gradually shift to the downstream and change after each flood season. This phenomenon is often found in the small alluvial grounds along the Mekong river and in the downstream of the Bassac river. Islands are formed by the growth of alluvial grounds, which enables them to achieve the real stability. However, these kinds of islands are usually small in size. Another kind of islands, which are in larger size, are composed by the flow cutting and the establishment of a new flow process, such as in the islands of Cai Vung and Tay (Fig. 2) on the Mekong river, several islands on the Ham Luong and Co Chien rivers, the islands of Vinh Truong (Fig. 3), and Dung (Fig. 4) on the Bassac river. These islands are often quite stable. In the case of Dung island on the Bassac river, which is located between two large distributaries, it gets expanded significantly through time with a big amount of annual sedimentation. The formation of alluvial grounds and islands is one of the typical morphological characteristics of the Mekong and Bassac rivers.

Fig. 2. Islands formed by the flow cutting phenomena on the Mekong river.

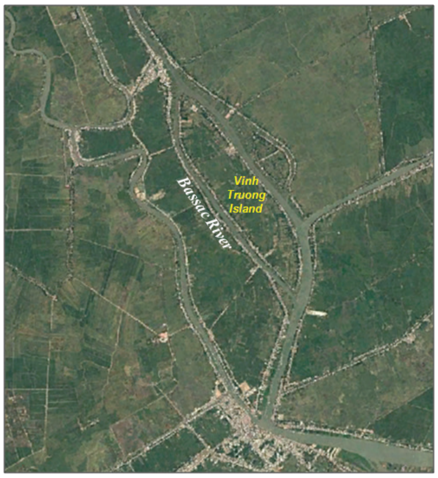

Fig. 3. Vinh Truong island formed by the flow cutting phenomena on the Bassac river.

Fig. 4. Dung island formed by alluvial deposition phenomena on the Bassac river.

The formation of the grounds across the rivers: across ground is a type of relatively stable structure in the riverbed, often in the form of a diagonal edge across the river that is formed by the alluvium. The across grounds are formed on the quite stable and slightly wavy river segments, and so, in the Mekong river, these grounds are often found at about 100 km from the estuaries.

The change of the depth along the rivers and the formation of abysms: in the delta, the depth of the river greatly depends on some flow factors. The river bottom is often raised in most of the rivers in the Mekong delta by approaching the estuaries. Within about 60 km from the mouths, the bottom depths are quite stable and leaned trend in the upstream on both the Mekong and the Bassac rivers. The river beds are wide and shallow (except the Ba Lai and the Ham Luong rivers, the bottom depth is only with the leaned trend from the mouth to the upstream, and there is no big change at river mouths). The deepest places and the big changes usually happen in the distance of 60 km from the estuary to the upstream. This is a complicated segment, as it is directly affected by the strong water flow in the flood season and the contrary between the upstream and the tidal flows during the dry season. At a distance from 60 to 140 km, both the rivers have the lowest average bottom depth, although there are several places of elevation at -25 and -35 m. The biggest abysms of the two rivers are found at a distance of 140 km to the upstream. On the Mekong river, that is where the curved segment at Tan Chau is present, with a depth of -45.1 m and on the Bassac river, that is present after the Vam Nao connection, with a depth of -40.6 m. In these segments, the bottom depth trend is gradually raised in both the rivers (Table 3).

Table 3. Characteristics of the bottom depth in the Mekong and Bassac segments.

River	Segment	Distance (km)	Maximum depth (m)	Minimum depth (m)	Average depth (m)
Mekong	Estuary	0-60	-16.3	-7.4	-10.0
	Middle	60-140	-35.3	-6.5	-17.3
	Upper	140-220	-45.1	-9.0	-15.5
Bassac	Estuary	0-60	-16.0	-8.4	-12.5
	Middle	60-140	-28.7	-9.6	-16.6
	Upper	140-220	-40.6	-5.1	-13.6

(Sources: The data are summarized from [1] and lots of other sources and at different moments).

Trend of river banks and coastlines changes during the past 100 years

Researches from the spatial images and the river and coastal topographic surveys in the Mekong delta show that the general trend of morphological change of the Mekong and Bassac rivers during more than 100 years are the flow shifts, island formation and accretion, flow division and incorporation, main stream swerve for the divided flows, estuary siltation, and gradual sea encroachment by alternation of the alluvial deposition and erosion process.

The flow shifts appear at many places on the river system,

Fig. 5. Changes of the islands between Dai and Tieu mouths on the Mekong estuary from 1906 to 2016 [Sources: Bibliothèque nationale de France (1906), U.S. Army (1972), and Google Maps (2016)].

such as the Mekong river at Cao Lanh (deviation of 3-4 km to the right), the Ba Lai river from 12-20 km to the estuary (deviation of 2.5 km to the right), the Bassac river at Long Xuyen-Thot Not segment (deviation of 1.0 km to the right), and the Vam Nao river at the segment closed to the Mekong river (deviation of nearly 1.0 km to the upstream). The formation and accretion of islands happen in most of the rivers, including the shift and the expansion of islands and the sedimentation and connection of small islands into the larger or with the major ones. Typically, this is applicable to the islands of Long Khanh, Gieng, the small islands from Cai Be to Vinh Long on the Mekong river, and the islands of Ong Ho, Cac, May, and Dung on the Bassac river. The swerve of the main streams is probably the biggest activity of the river system during the past 100 years and can be considered as the final stage of the flow division/incorporation process. This process is often correlated with the flow shifts, such as at Cao Lanh and Sa Dec on the Mekong river and Long Xuyen on the Bassac river. The alluvial deposition at the estuaries is also a special activity in the Mekong river system. The most typical alluvial deposition activities are at the entrances of the Co Chien and Ba Lai distributaries on the Mekong river and the Dung island on the Bassac river. During the past 100 years, there has also been a considerable variation in the coastline, with the general trend in sea encroachment being 2-4 km, even 7-8 km, on an average. The biggest changes are the connections of the islands between the Tieu and Dai estuaries with the Ilo Ilo island (in the offshore), 3 km far from each other, to create a new shoreline (Fig. 5), sedimentation and stretching out the Dung island toward the sea 2-6 km, along with the disappearance of the Bat That's mouth (Fig. 6), extended the shoreline between Ham Luong and Co Chien and the My Thanh river's right bank promontory, deeply eroding the shoreline up to 1-3 km, accompanied with the disappearance of a series of coastal small islands from My Thanh to Ganh Hao, stretching to Mui Ca Mau up to about 10-15 km to the sea.

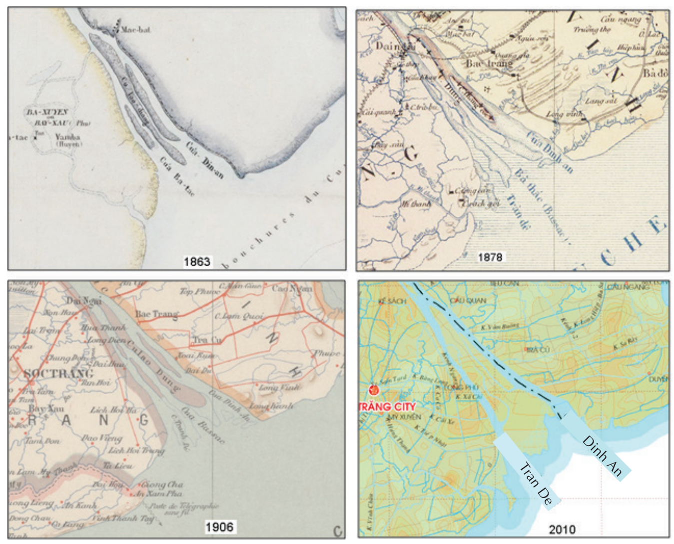

Fig. 6. Changes of Dung island on the Bassac Estuary from 1863 to 2010 [Source: Bibliotheque nationale de France (1863-1906)/Department of Survey, Mapping and Geographic Information Vietnam (2010)].

Trend of river bank and coastal changes during the past 30 years and recent time

The general trend of the rivers' morphological course during the past 30 years was erosion and sedimentation along the rivers at different levels. This change has directly increased or decreased the cross-sectional area of the river. Such changes in accordance with the rules of the non-stop movement of the curved river segments, alluvial grounds, and deep channels. The cross-sectional area surveys for both the Mekong and Bassac rivers show that a general trend is increase in the area (0.1-0.4% per year) and decrease in the width (3-5 m per year). This conflict proves that the river bank becomes stable and the cross-sectional area is expanded only by digging deep the riverbed. However, the morphological course of the cross-sectional areas shows that the ability to deeply dig the stable bottom ground is harder than the eroding the river walls, leading the river bank to have an increase in the vertical trend.

In all the rivers' morphological characteristics, perhaps the depth along the rivers has little change than others, except for some extra tributaries. The sustainability of the riverbed proves that the flows have been dug to the deepest area by allowing the possibility at each location.

The biggest changes recorded by the spatial images and the actual measurements are the shifts or the connections to the islands on the Tu Thuong-Cao Lanh and Cai Be-Cho Lach segments. This includes the shift of a small island 2.0 km from the middle to the lower region of Tu Thuong, connecting the Ma island and another small island in the upper region with the Tay island, connecting two small islands with the Gieng island, and connecting the islands at the Cai Be-Cho Lach segment with the islands between the Tieu and Dai mouths. The morphology of the islands on the Bassac river from the upstream to Dai Ngai are quite stable, except for some small changes, such as the extension of the Thi Hoa island and the agglutination of the island at the Can Tho ferry into the right river bank. The most meaningful change on the Bassac river has been the development of the Dung island at the estuary and the continuing sea encroachment at an average speed of 20-50 m/year. The islands in the Ham Luong and Co Chien rivers seem to be stable. The Con Co island and another small one was merged with a bigger island between the mouths of Co Chien and Cung Hau. Some islands at the entrance of Co Chien on the Mekong river (opposite with Vinh Long province) were also interconnected to fill up quite a large mouth in the past (Fig. 7).

Fig. 7. The coastal erosion at Rach Goc and Ho Gui (Ca Mau province) from 1984 to 2016 (Source: Google Maps).

The general trend in coastal change is still the sea encroachment in the shoreline of the estuary and the alternation between the slow sedimentation and erosion processes in the other shorelines during the past dozens of years. The annual average sea encroachment velocity is about 10-20 m per year. The fastest sea encroachment happened from Mui Ca Mau to Bay Hap with an average speed of 30-50 m per year. The shorelines at Vam Cai Cung (Bac Lieu), Dong Hoa (U Minh Thuong), and Rach Gia also encroached to the sea at a speed of 5-10 m per year. In contrast, some shorelines of Ganh Hao-Mui Ca Mau and Rach Gia-Ha Tien were eroded at the same speed. The morphological change in the shallow territorial waters is quite large due to the move of the subterraneous sand dunes, which continuously occurred after the flood seasons and due to the strong wind spells (Fig. 8).

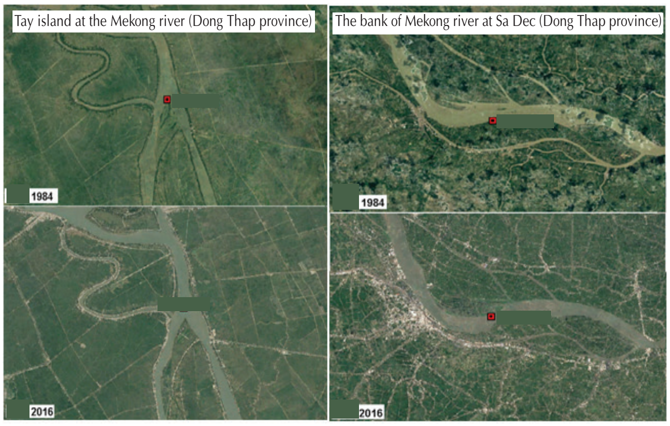

Fig. 8. The erosion at the Tay island and the Sa Dec bank on the Mekong river from 1984 to 2016 (Source: Google Maps).

In recent years, along with "salinity intrusion" and "drought", the "erosion" has become the most "important and necessary" problem in the Mekong delta, whereas "flood and flooding" seem to be less interested.

During the recent 15 years, the erosion situation has become more complicated, occurring at many places in the river, for instance, in the canal systems and in most of the coasts in the Mekong delta. The most common is along the Mekong river banks (from Tan Chau-Hong Ngu to the estuaries) and in the island system (Long Khanh, Tay, Gieng, Dai, and Phung) in the provinces of An Giang, Dong Thap, Vinh Long, Tien Giang, Ben Tre, and Tra Vinh, along the Bassac river banks (from Long Binh to the estuaries) and the island system (My Hoa Hung, Tan An, and Dung) in the provinces of An Giang, Vinh Long, Soc Trang, Tra Vinh, and Can Tho, the coastlines in the provinces of Tien Giang, Ben Tre, Tra Vinh, Soc Trang, Bac Lieu, Ca Mau, and Kien Giang, in the canal systems in the provinces of Dong Thap, An Giang, and Ca Mau, in the connecting rivers/channels of the Mekong and Bassac rivers, especially the Vam Nao river (An Giang). According to the preliminary statistics, in the whole Mekong delta, there are about 1,000 places with erosion, including nearly 300 serious sites, more than half of which are on the main rivers [2].

Instability causes of riverbeds and the coasts, and the current erosion principal trend

Annually, the average discharge from the upstream of the Mekong river basin into the Mekong delta is about 13,700 m3/s [3], and it is quite stable from year to year. However, the seasonal changes in a year are somehow large. The differences in the flow between the flood and the low-flow seasons are 7.42 times (24,500 m^3/s and 3,300 m^3/s) [3] and between the highest month (September) and the lowest month (April) are 18.0 times. This rate is not reduced significantly by the regulation of the Great Lake. In the flood season, the river banks are overwhelmed due to the overloading of the riverbed. In the low-flow season, all the rivers are strongly affected by the high tides due to a scanty water source. The early flood flow plays an important role in creating the river bed form, due to being maintained during a sufficiently long time and through stable erosion, which is only concentrated in the riverbed. In the middle of the flood season, especially during the high flood years, the deep pit digging ability and the erosion of the river banks (particularly in the curved river segments) are increased by the high velocity flood flow concentrated in the riverbed. Another major impact of the water flow is the conveyance of the sediment. If the strong flows at the beginning and middle of the flood season (maximum velocity 2.0-2.5 m/s) are the principal causes of deep digging and sediment take away, then the flow reductions at the end of the flood season (average velocity of 1.0-1.5 m/s) are the major causes of siltation along the rivers, especially in the estuaries, so that there are many changes in the river form after a flood season.

The tide of the East Sea with a large amplitude is propagated very far to the upstream of rivers. In the low-flow season, the tidal fluctuation is still seen at Phnom Penh, more than 300 km away from the Mekong estuary. The tidal fluctuation makes the river bank always in wet or dry situations, creating favorable conditions for the river banks to have steep, porous, and crumbly soils and get easily eroded. Closer to the river upstream, in spite of the decreasing effects of tide, due to the river flow being operated by the accumulative/discharge phases of tidal flow, there have been certain effects on the process of erosion and siltation. In addition, a very strong velocity of the

Fig. 9. Some pictures of erosion at river banks and coasts in the Mekong delta (Source: individual information, e-newspapers, and the Internet).

opposite tidal flow at the nearly estuarine areas (0.7-1.5 m/s) also contributed to the instability of the riverbeds (Fig. 9).

The agglomeration of materials in the salt water environment is also a cause of sedimentation at estuaries.

Annually, a strong wind that blows from sea to inland, opposing the flow direction of the main rivers, is called the "Gio Chuong-strong wind", which often appears from October to April in the Mekong delta. This strong wind usually appears frequently and strongest during February, then decreases until the end of the season. The average speed of Gio Chuong is from 4 to 6 m/s (at a frequency of 40-60%), sometimes reaching 9-10 m/s (at a frequency below 5%). When blowing into the wide and airy estuaries, the wind speed can reach up to 10-15 m/s, even 20 m/s. The estuarine water level rose due to the strong wind when combined with the high tide peak. According to surveys and calculations, the water level rise is about 20-30 cm, even up to 50 cm. With wider and airier estuaries, the winds in the Bassac and Co Chien rivers are stronger than others. Further inland, although the wind speed and appearance frequency decreased remarkably, but the strong wind still made big waves crash into the river banks that were always wet, causing strong erosion even in the dry season. Within a distance of 100 km from the mouth, the erosion of river banks by strong wind might be greater than that by flooding. At Sa Dec, the erosion of the river banks mainly occurs during the receding flood and wind strong period (from October to December). In addition, other impacts of strong wind are supporting for siltation and shifting submerged sand dunes move before the estuary, erosion and alluvial accretion along the coasts.

The ocean currents also have a certain role in the morphology of shorelines and shallow water. In the dry season, the Northern Hemisphere currents press onto the shores and at the end of the flood season carry the estuarine sediment to accrete in Mui Ca Mau. During the rainy season, the Southern Hemisphere currents take the opposite direction, causing most sediments during floods to be deposited right at the river mouths.

The sediment is a vital element of the flow characteristics. The amount and the size of the sediments play a major role in the alluvial deposition in rivers, estuaries, and along the coasts. Every year, the Mekong delta receives about 150 million tons of sediment, on which, 138 million tons is in the Mekong river and 12 million tons is in the Bassac river, mostly in the flood season [3]. The average sediment content of the flood season is about 500 g/m^3 on the Mekong river and 200 g/m^3 on the Bassac river, according to the measured data [3]. However, the sediment content changes largely by time and space. The analysis results have shown that the sediment size of the Mekong river is bigger and more uniform than that of the Bassac river. The average diameter of sand grain in the bottom of Mekong river is 0.23 mm at Tan Chau, 0.21 mm at Sa Dec, and 0.20 mm at Vinh Long. From Vinh Long (Mekong river) and Can Tho (Bassac river) to the estuaries, the alluvial sedimentation phenomena begin to occur very complex as forming newly emerged alluvial grounds, accreting, and extending the old islands to the estuaries. The rest would be deposited to form estuaries with many sand dunes. For the finer particles, a part would be conveyed further in a high salinity water area, agglomerated and sunk down in shallow water before the estuary, whereas the other part would be shipped to the South for the consolidation of Mui Ca Mau. When going into the fields, both on the Mekong and Bassac rivers, most of the sediment is deposited at a distance of 10-20 km far from the river banks. This sedimentation made the river banks increasingly higher and formed the new soil dunes along the rivers.

The biggest changes of river morphology in the Mekong delta during the past hundred years, particularly in recent 30 years, have mainly been caused by human activities. The uncontrolled exploitation of the forests, construction of reservoirs in the upstream, digging and expansion of the canal systems, embankment along the rivers and canals, the construction of sluices and dams at the entrance of canals, dredging river channels to enhance the ability of ship traffic, and reinforcement of river banks for erosion protection have been the interventions, direct or indirect, in the morphological changes of rivers. In that, the exploitation in the upstream of the Mekong river basin is the most meaningful of all.

As mentioned above, the almost sediment yield of the Mekong delta is mainly generated by the upstream flood flow. In the past natural conditions, within an average of 10 years, there were 3-4 years of weak flood, 3-4 years of medium flood, and 3-4 years of high floods. During the weak flood years, due to the low sediment yield, the estuaries and shorelines often occur at the erosion rates of 5-20 m/year. During the medium flood years, the riverbeds and shorelines are quite stable by an insignificant erosion and accretion of tides, strong winds, and currents. During the high flood years, while the river affected by strong erosion, the coasts have a trend of accretion by a big amount of sediment to the estuaries, at a rate of tens of meters per year. Therefore, during the 10-year average, the upper parts of the rivers are not only accreted but also eroded at different levels; the estuaries and coasts even thought of an alternative accretion/erosion phenomenon but still are the general gradual sea encroachment trend (encroached about 100 m during 3-4 years of high flood and eroded about 30-40 m during 3-4 years of weak flood; during the 10-year average, still encroached to the sea about 60-70 m).

However, in the past 20 years, especially after three consecutive high floods in 2000, 2001, and 2002 in the Mekong delta, the changes in the flood sequences have some significant considerations, leading to huge impacts on the sedimentation and erosion of the riverbeds and coasts. In 13 years (from 2003 to 2016), except for the rather large flood in 2011, almost of the duration were only occurred with the medium floods (2004, 2005, and 2013), below the medium floods (2006, 2007, and 2009), weak floods (2008 and 2014), very weak floods (2010, 2012, and 2016), and extremely weak floods (2015). In 2011, the high amount of sediment was not enough to compensate for the accumulated consecutive shortage eight years before and five years after it [4].

According to the calculations, with the impacts of hydro-power system on the upstream of the Mekong river and the decrease in sediment due to weak floods, at an average of the past 10-15 years, the volume of the upstream sediment into the Mekong delta is around 60-70 million tons/year (40-50% compared with the previous average) [5]. Thus, the upstream river segments always have a shortage of sediment and imbalance of kinetic energy, which is the cause of the increased erosion phenomena. In particular, the medium and below medium floods with the flow of riverbed creation are maintained for long periods (3-4 months), causing a strong capacity for the erosion, respectively. This phenomenon is also spread into the canal system. At the estuaries and coasts, because of no sediment deposition, the erosion phenomena occur consecutively instead of alternating with sedimentation as before, conceiving the general trend of soil erosion, with an average speed of 2-5 m/year. In the past 10 years, some places were eroded inland not less than 100 m (Rach Goc, Ho Gui-Ca Mau) - some places have even turned from siltation before to erosion now (Mui Ca Mau).

In addition to that, the early flood (August) brings more sediment than the other periods in the Mekong delta. Sediment descends at the end of the flood season. About 60-70% of the total sediment into the Mekong delta is concentrated in the first two months of the flood season, namely, July and August [6]. At this moment, the flood water is needed to be stored early in the most of the upstream Mekong reservoirs to ensure its being fully filled from the end of August to early September. Therefore, the major part of the water flood and sediment is retained in these reservoirs. In the remainder of the sediment to the lower by flood flow, more than half of it flows back into the Great Lake. Until the Great Lake is filled with water (at the last September for medium and weak floods), the flood just starts from the Great Lake to complement into the Mekong delta, but almost all flood water has run out of sediment currently. Thus, it might be understood to be the reason behind why the erosion phenomenon has increased.

In addition, an important cause of the increased erosion is sand mining along the rivers from the lower region near the estuaries to the upper region near the Vietnam - Cambodia border, with a mass of millions of tons/year (according to the unofficial synthesis, the licensed exploitation of the sand can be up to 12-15 million m^3/year, excluding the illegal exploitation). Thus, the total remaining amount of sediment for functions of “accretion” for rice fields and “stable” rivers and coasts in the Mekong delta is only 40-50 million tons (30-40% less than before) [5, 7].

Due to the multiple impacts from the nature and humans, the erosion in the Mekong delta in the recent years has begun to form the following notable trends:

Moving closer to estuaries for coastal erosion: if the erosion often occurred at the coasts about 100 km far away the estuaries before, nowadays, due to the limited amount of sediment, the erosion phenomenon is approaching following an asymptotic pattern toward the estuaries, such as at Binh Dai (near the Dai estuary, Ben Tre), Duyen Hai (near the Cung Hau estuary, Tra Vinh) on the Mekong river, Vinh Chau (near the Tran De estuary, Soc Trang) on the Bassac river, and Dong Hai (Ganh Hao estuary, Bac Lieu) on the Ganh Hao river.

Erosion happening year-round, especially in the dry season: previously, erosion often happened from the middle of the flood season (September to October for the weak and medium floods) to the end of the flood season (November to December for the high floods), at a frequency of up to 90%. However, now, the erosion occurs almost year-round, with a trend leaning toward the dry season (due to more influence of the tide).

More serious erosion in the connecting rivers/canals of the Mekong and Bassac rivers: formerly, the erosion phenomenon happened almost rarely (or not too seriously) in the connecting rivers/canals of the Mekong and Bassac rivers. However, now, due to the changed hydraulic balance between the rivers, there is a trend of the flow moving from the Mekong river to the Bassac river, causing increased erosion in the almost river/canal system, especially in the Vam Nao river [6].

Ever-increasing serious level of erosion: some years ago, a serious erosion occurred once every 5-10 years (on the Mekong river in 1991 at Hong Ngu, in 2000 at Tan Chau, and on the Bassac river in 2012 along the National Road No. 91 from Long Xuyen to Chau Doc). However, nowadays, almost every year, a serious erosion occurs, from the coast at Ganh Hao (Bac Lieu), Duyen Hai (Tra Vinh), Ho Gui (Ca Mau), and Go Cong (Tien Giang) to the river banks at Cho Moi, Tan Chau (An Giang), Thanh Binh, Hong Ngu, Sa Dec (Dong Thap), and at the infield canals at Thoi Binh, Dam Doi, Cai Nuoc (Ca Mau), Hong Ngu, Thap Muoi, Thanh Binh, Lap Vo (Dong Thap), Tri Ton, Phu Tan, Tinh Bien (An Giang), O Mon, and Phong Dien (Can Tho) (Fig. 10) [5].

General trend of the erosion phenomenon is to continue developing, both in terms of width and depth in the coming years: this general trend might be dominated from the coasts to along the rivers and canal systems year-round, from the flood season to the low-flow season, expanding from the flood to the tidal area, getting distributed from the large rivers to the small canals, happening on the whole Mekong delta, from the Plain of Reeds (Dong Thap Muoi), Long Xuyen Quadrangle, and between the Mekong and Bassac rivers, to the Ca Mau Peninsula and in the entire coastal strip. The level of erosion can be slight, medium to serious, or even very serious.

The basic solutions for the erosion problem of rivers and coasts in the Mekong delta

To attain effective and sustainable responses for the existing erosion situation of rivers and coasts in the Mekong delta, the following basic solutions should be considered and implemented:

1) Close cooperation with the riparian countries situated at the upstream of the Mekong river basin on river basin management, especially in the fields of hydro-power

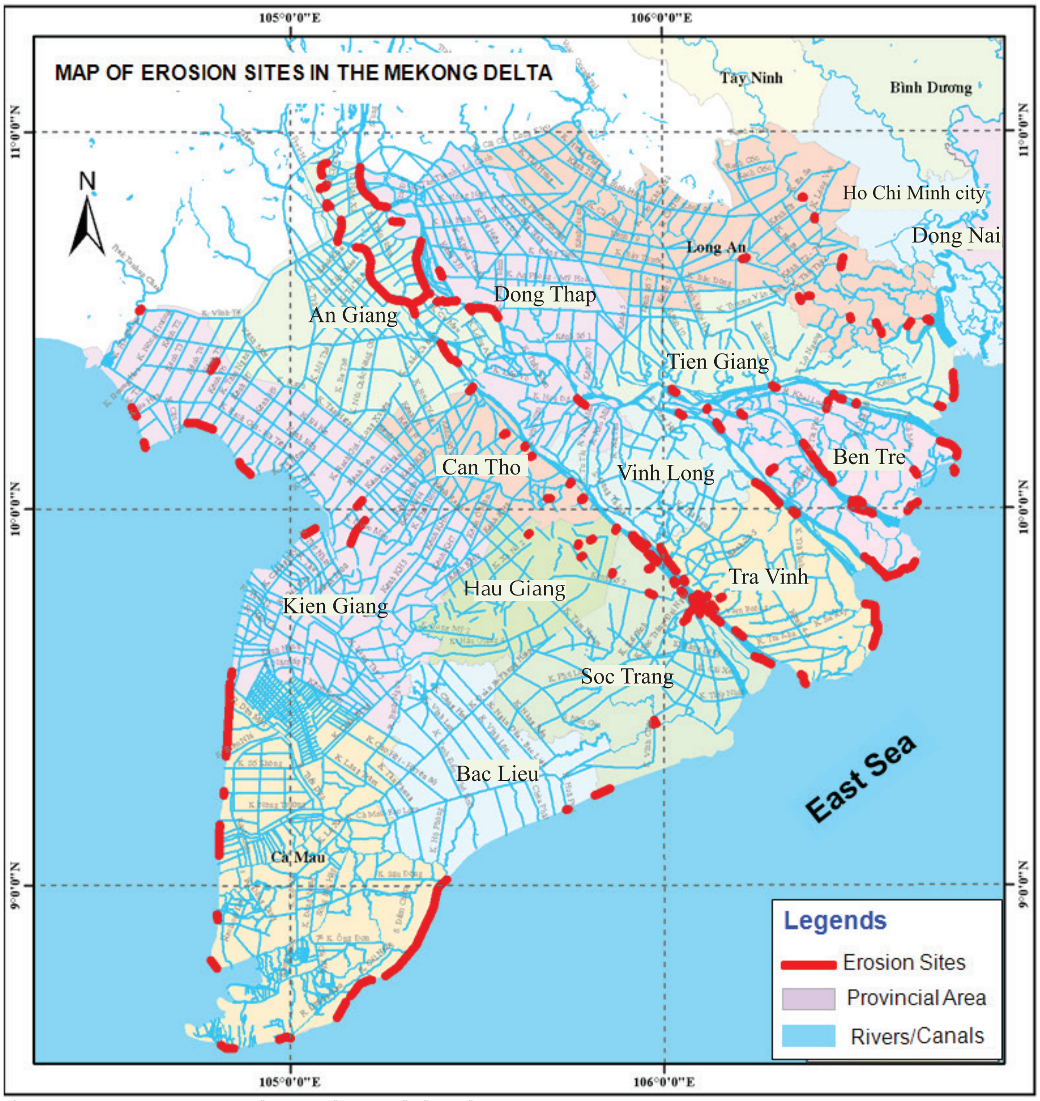

Fig. 10. Map of erosion situation in the Mekong delta during 2016-2017 (Sources: Southern Institute for water resources planning, 2017).

development (size determining, designing, constructing, and operation processing for reservoirs), management and development of forests, agriculture, and infrastructures.

2) Management and licensing restrictions on sand mining in rivers. The rigid prohibition and prevention of illegal and contraband sand mining activities.

3) The rivers and canal banks should be reinforced by traditional measures with local materials (melaleuca pile and bamboo) and trees should be planted for wave protection, which can be an early initiative for the protection activities of all the rivers and canal banks, that would constitute planting mangroves to protect sea dykes and the coasts, including the uneroded places. In the coasts, depending on the nature and the characteristics of the erosion areas, we can apply the traditional and inexpensive structural solutions, such as creating the grid layers of wave prevention or soft embankment by melaleuca or bamboo piles (according to the form of the alternate wave preventive layers, T-shape, and improved T-shape) for the erosion protection or sedimentation increase.

4) The erosion situation should be surveyed and comprehensively evaluated to gauge the stability of rivers, canals, and coasts. The development trend of rivers, canal banks, and coasts with the changes in the flow and sediment content in flood and low-flow seasons under the impacts of sea-level rise, climate changes, upstream development, and other related disasters should be researched.

5) The strategies for river, canal bank, and coast management and protection should be built. Henceforth, reasonable and feasibility solutions for the relocation, strengthening, and protection activities (according to different measures) for the entire river, canal, and coast system should be proposed, based on the overall and harmonious perspective on the economic,

social and investments, capital allocation for each stage, each region, and each river segment.

6) Consideration to balance for all the problems (capital source, technical feasibility, importance level, impacts of upper/lower, and the entire system) to define the number of priority-protected sites/segments on the river/canal banks and coasts.

7) Solutions for housing along rivers, canals, and coasts by different materials, forms, and structures should be researched to enhance the sustainability and stability, both in the building structures and shoreline stabilization.

8) A safe corridor for the inhabitants, welfare structures, and infrastructures along the rivers, canals, and coasts should be established to closely manage the use and socio-economic development related to the rivers, channels, and coasts.

9) The welfares and socio-economic development programs should be combined to layout and relocate inhabitants along the rivers, canals, and coasts.

10) Solutions should be proposed to protect or relocate the initiative infrastructural structures (especially roads) in the high-risk erosion areas.

11) Establishing river treatment planning, river and coast space organizing, and zoning river and coastal functions to management, exploitation, rational and sustainable use of rivers and coasts should be conducted.

Conclusions and recommendation

Erosion of the rivers and the coasts is a natural phenomenon, especially with a young river and an accretive coast as the Mekong delta. Under the impacts of human activities, the erosion becomes more and more complicated. Though there exist many causes of the river and coastal erosion, however, the most fundamental cause is flood flow and the amount of sediment in the rivers. The changes in the upstream of the Mekong river basin in the last 20 years have been the main causes of the flood flow and sediment concentration fluctuations in the Mekong delta. This is also the basic and direct cause for increase in the erosion phenomenon of the rivers and the coasts during the recent years. In addition, sand mining on a large scale and unreasonability about space and time is also a cause of serious erosion in the river segments. In addition, the sea-level rise, increase in the peak tide, strong winds, and high waves are also some of the root causes behind the more complicated erosion processes in many river segments and coasts. In certain structures of natural disaster protection, the erosion preventive structure has the highest cost and risk. Consequently, the economic, social, engineering, and environmental factors should be considered satisfactorily before making an investment decision for the river and coast protection constructions. The combination or separation between the structural and non-structural measures, between the works of local materials, between the inexpensive and the temporary with the constructions of strong, high investment capital and durable structures are considered to be reasonable solutions. For the coast, even planting mangroves is a good solution to protect the banks, but it cannot be implemented to achieve the desired effects anywhere or at any time. Careful survey of each of the coastal section, during each appropriate period, as well as the effective preventive solutions of the ocean waves must be considered importantly before planting.

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