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Change in sedimentary environment at Kim Son coastal plain - Ninh Binh

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Abstract
Kim Son coastal plain is a part of the Red River Delta located between Day and Can rivers. Over the past 55 years, Kim Son coastal plain has been the region with the highest accretion rate in the Red River Delta. This study aims to clarify the sediment characteristics of Kim Son coastal plain. It has the structure of a typical tidal flat and a relatively straightforward tide-influenced sedimentary structure evidenced by the field observation, sampling 70 hand-drilled boreholes, borehole logging and analyzing 177 samples of grain size. There are three tidal sedimentary zones to be identified, including sand flat, mixed flat, and mudflat. The history of topographic changes is also presented over six periods from 1965 to 2020 based on analyzing and interpreting multi-time satellite images. The total accretion area of Kim Son coastal plain over 55 years was 4,081.2 ha.

Keywords: Sedimentary environment, coastal plain, accretion, Kim Son - Ninh Binh.

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INTRODUCTION

Kim Son coastal plain is located between Day and Can rivers, having seaward developing direction with a shoreline length of 18 km. The development of Kim Son coastal plain is associated with the formation and development of the Red River Delta as well as the land reclamation. In 1829, after nearly 200 years, Kim Son beach encroached on the sea more than 20 km. Kim Son has undergone many times the embankment of the sea dike with 3 dike systems: Binh Minh I dike system (10 km long) built in the event of the liberation of Ninh Binh province and completed in 1959; Binh Minh II dike system (22.8 km long) formed in 1980; and Binh Minh III dike system established in 2000. Binh Minh IV dike system is being constructed.

After more than 50 years, Kim Son coastal plain has been one of the fastest accreting areas in the Red River Delta, with speed from 90 m/year to 110 m/year [1–3]. The strong development of the Kim Son coastal plain also attracts many interested scientists, it is timely updated with data on shoreline changes, projects for the development of shoreline and mudflats,... In general, most of the works have only mentioned the shoreline changes caused by erosion-accretion activities.

This paper is to analyze the coastal plain structure based on hand-drilled boreholes (70 boreholes), characteristics of grading component in the cross-sections, and the assessment of topographic variation based on multi-time images to clarify sedimentary environment changes in Kim Son coastal plain.

OVERVIEW OF THE STUDY AREA

Wave mode

Wave mode is strongly influenced seasonally by the wind directions and conditions. In the winter, the wave has the main direction of East and Northeast (frequency 51.7%, average height of 0.1–0.4 m). In summer, the prevailing direction is southward (37.6%), average height of 0.1–0.45 m [4–6]. In general, waves in summer are higher than in winter due to the strong influence of storms and tropical depressions.

Tidal regime

The tidal regime in the study area has the characteristics of the Northern Delta coastal plain. Maximum amplitude can reach 2.0–2.5 m, averaging 1.4 m. During the high tide, the diurnal character is dominant, a peak and a tidal foot appearing every day. However, the difference in time of rising and falling as well as time of getting the peak and base is unstable. This shows the heterogeneity of the tidal regime in the study area. In general, the tidal regime in the study area is intermediate between the heterogeneous diurnal regime and the mixed diurnal tidal regime.

Sedimentary characteristics of Kim Son coastal plain

Kim Son coastal plain is composed of modern intertidal sediments that are classified as Thai Binh Formation (Q_2^3tb) of Late Holocene age. The composition includes grey sand interbedded with brown silty clay layers and is characterized for an intertidal zone, varying from moderately to poorly sorted (So of 2.2–3.8). Paleontological relics find pollen spores and freshwater and brackish water diatomae such as *Acanthus* sp., *Acrostichum* sp., *Pinus* sp., *Japonica* sp., *Cymbella* sp., *Melosira* sp., *Navicula* sp., *Cocconeis sublittoralis*, *Paralia sulcata*,... [7].

According to Patricio et al., (2012) [8], in the wave-dominated coast, the grains tend to become finer seawards and the opposite is seen with tide-dominated coast. The coastal plain includes a lower sandy tidal flat, a middle mixed tidal flat and an upper muddy tidal flat.

MATERIALS AND METHODS

There are 70 hand-drilled boreholes drilled to 3 m deep below ground level on the Kim Son coastal plain. The boreholes are set evenly on the coastal plain area, according to the dike systems: Inside the Binh Minh I dike (7 boreholes), Binh Minh II dike (33 boreholes), Binh Minh III (17 boreholes), and outside the Binh Minh III dike (13 borehole) (fig. 1).

The borehole samples were taken as undamaged as possible to preserve the nature structure and sediment characteristics. The borehole stratigraphic columns were then built, and the boundaries of tidal flat sediments (sand flat, mixed flat, and mudflat) were defined. Tidal types and sedimentary sections were built on isometric maps. Fifteen boreholes had been analyzed for particle size in 3 typical cross-sections and 177 samples were analyzed by sieve and pipette method. For each borehole core, a sample was taken 25 cm apart and percentage of particle grade, medium grain-size (Md), degree of sorting (So), skewness (Sk) were determined.

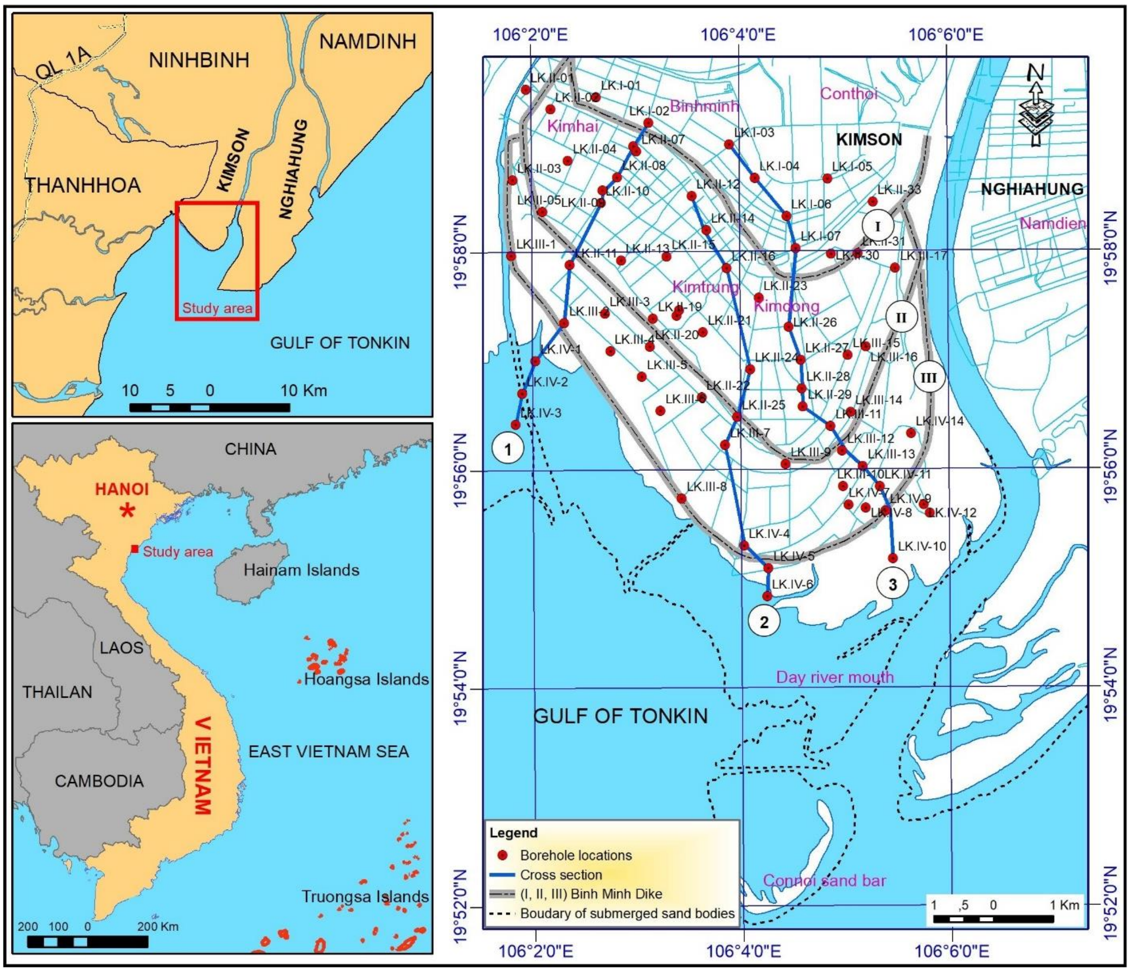

Figure 1. Maps showing the study area and borehole locations

Image interpretation of remote sensing method helps to determine the stages of topographic changes over time. Multi-time satellite images and topographic maps include UTM topographic maps at the scale of 1/50,000 in zone 48-Everest elliptical block published by the US Army Map Service (AMS) in 1965–1966, Landsat MSS satellite images (1973, 1975), Landsat TM satellite images (2001, 2003 and 2005), Landsat OLI satellite images (2013–2020), Spot-2 satellite images (1995), Sentinel-2A (2017–2020) and Sentinel-1 (2015 and 2017) (fig. 2).

Calculated shoreline was determined on satellite images according to the geomorphological signs. The shoreline is generally assigned as the boundary of the position of inundation at the maximum mean tide (excluding the case of meteorological conditions and waves). The orther special areas, the shoreline identified on the satellite depends on dike foot - sea embankment, coastal plain and coastal mangrove flora growing bruguierawith high density were considered. The satellite imagery is processed on image processing computer softwares such as Envi, PCI, Arc/View, Arc/Gis and Map/Info. The product is map of shoreline fluctuation of the Kim Son coastal plain.

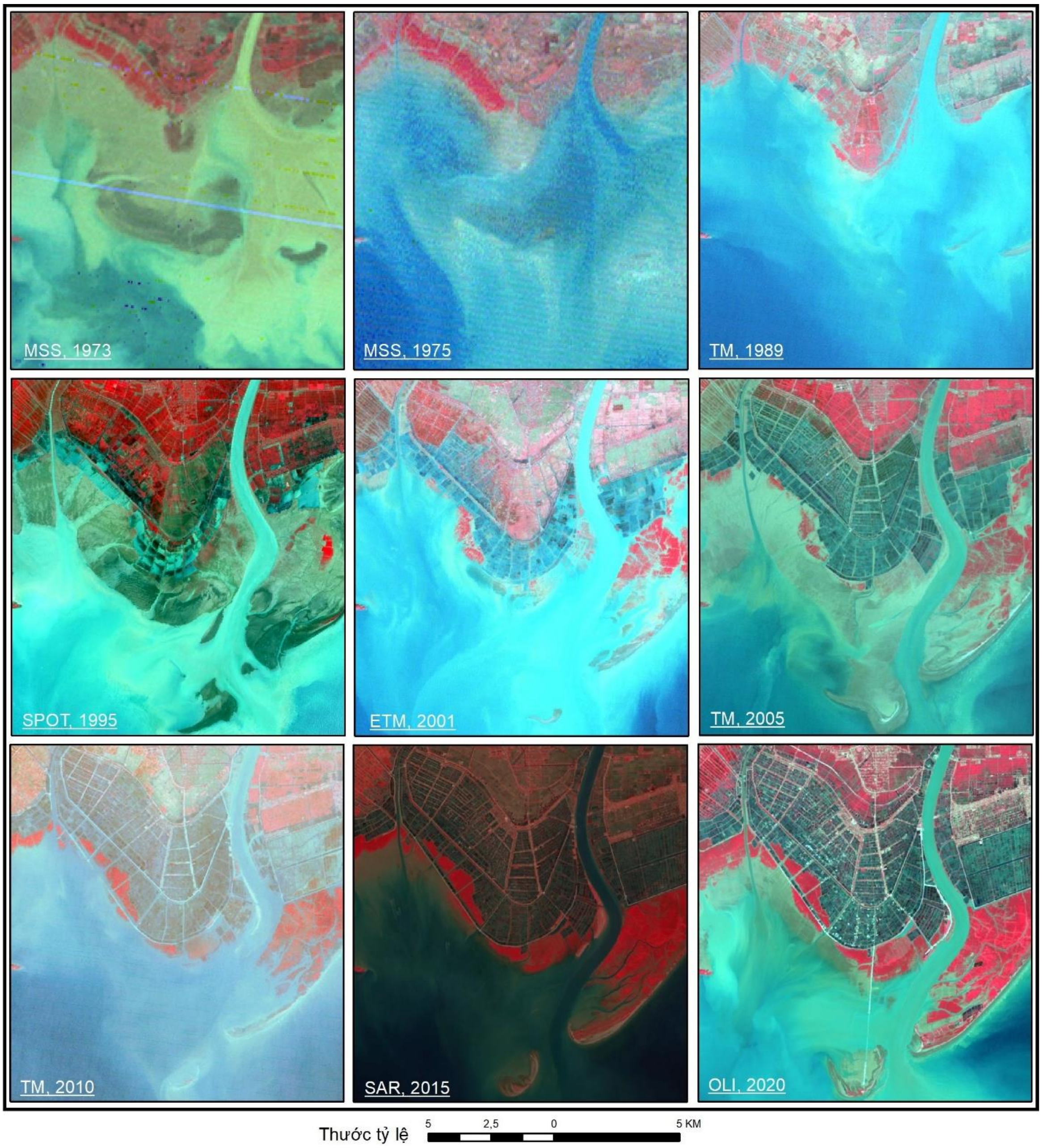

Figure 2. Satellite images in Kim Son coastal plain

RESULTS AND DISCUSSIONS

The analysis of sedimentary structure at 70 boreholes on Kim Son coastal plain and construction of geological cross-sections shows that Kim Son coastal plain is composed of sand flat, mixed flat, and mudflat. On the cross-sections and isometric maps, each location shows a different type of flat.

Sand flat

Figure 3. Sand flat deposits in LK.IV-9 (220–240 cm depth)

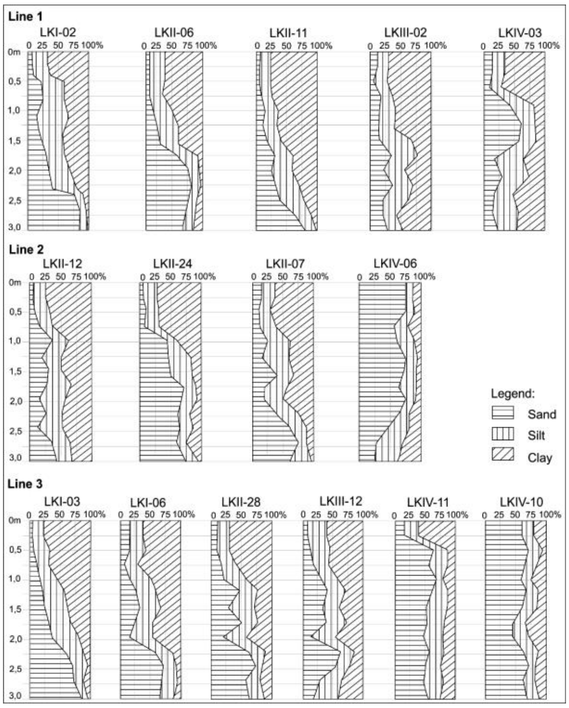

Figure 4. The composition of grain size graph in boreholes along the cross-sections

Sand flats occupy the lower zones of tidal flats, and are dominated by bedload transport of sand-sized sediments. They are the most variable intertidal areas in terms of both sedimentary facies differentiation and trace-fossil content, this variability is essentially controlled by the intensity of tidal currents in combination with wave action [9, 10]. In macrotidal settings characterized by high-current velocities, migration of large-scale bedforms (ie. two-dimensional and three-dimensional dunes) is the dominant process [11–13]. Deposits typically consist of medium to thick bedded, trough and planar cross-bedded coarse to fine-grained sandstone, and medium to very fine-grained sandstone with parallel lamination formed in the upper flow regime [12, 14, 15]. On high-energy sand flats, rapidly migrating bedforms generally preclude intense bioturbation (e.g., Baucon (2008); Mángano and Buatois (2004); Reineck and Singh (1980) [10, 16, 17]).

The sand flats in the study area occupy the lower zones of tidal flats (outside the Binh Minh III dike). Inside the Binh Minh III dike, sand flats were found in boreholes from 1.8–2.0 m depth (fig. 3). The composition of sand flats consists of sand (43.1–87.0%), silt (10.0–35.8%), and clay (2.0–35.4%); having sedimentological parameters: Md of 0.062–0.116, So of 1.298–2.814, Sk of 0.381–0.840 (figs. 4–5).

Mixed flats

Mixed flats occur across the transition between sand flats and mudflats, and are characterized by alternating bedload sedimentation and fallout from suspension [18]. Deposits typically consist of thinly interbedded wave- and current-ripple cross-laminated, very fine-grained sandstone and massive or parallel-laminated mudstone. Flat-topped ripples and washout structures may also be present. The intensity of bioturbation is typically moderate [10].

Mixed flat is widely distributed in the outside Binh Minh III dike (0.5–0.6 m thick). However, the normal thickness is from 1.5–2.0 m, some special area from 2.5–3.0 m thick (fig. 6).

The distribution of mixed flat sediments on the isotropic diagram shows that the sediment thickness changes over time. During periods of pre- and post-construction of the Binh Minh I dike, the sediment thickness in central part is greater than that on both sides of the edge (adjacent to Day and Can rivers). However, the late period witnesses the opposite (fig. 7). The characteristics of mixed flats are sand, silt, interbedded clay (parallel or ripple structures). The mixed flat consists of sand: 11.0–63.3%, silt: 16.9–52.7%; and clay 14.1–66.3%; having sedimentological parameters: Md of 0.042–0.06, So of 3.013–5.586 and Sk of 0.191–0.763 (fig. 4–5).

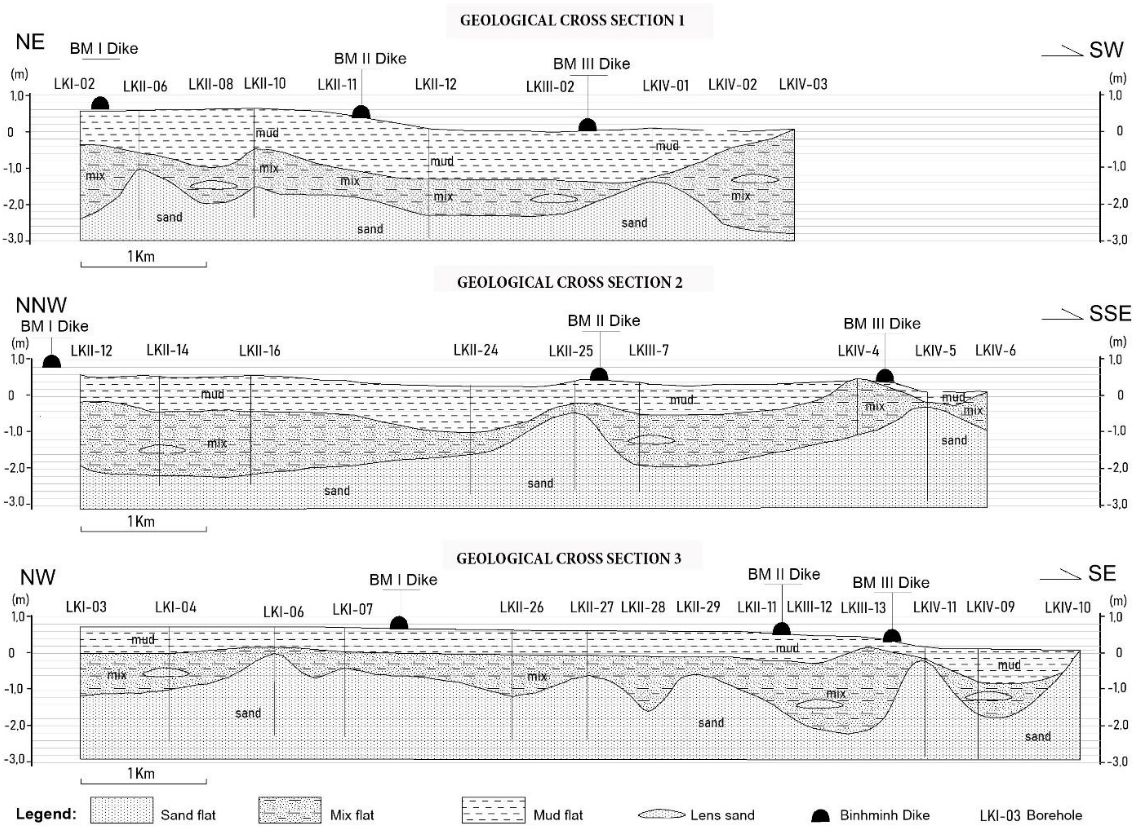

Figure 5. Geological cross-sections of Kim Son tidal flat deposits

Figure 6. Mixed flat deposits in LK.III-9 borehole (230–250 cm depth)

Mudflats

Mudflats constitute the upper zone of tidal flats, with depositional processes dominated by the fallout of suspended sediment comprising sortable silts, flocs, and aggregates [18, 19], as well as biodeposition due to the production of fecal pellets and pseudofeces [20–22]. Mud flat deposits are dominated by parallel-laminated or massive mudstone, while lenticular-bedded siltstone and very fine-grained sandstone are less common. Salinity shifts, together with changes in exposure and temperature, are typically dramatic in the upper intertidal zone [23, 24]. Modern mudflats are intensely bioturbated with polychaetes, gastropods, and bivalves being common producers [10, 25].

In the study area, the mudflat sediments cover the mixed flats or sand flats (fig. 8).

However the thickness differs depending on the location. The thickest area is in the west (bordering Can River), and thickness tends to decrease gradually from Can to Day rivers (fig. 7). The mudflat deposits are dominated by parallel-laminated mudstone and intensely bioturbated by polychaetes, gastropods. The results of analyzing the composition of grain: Sand 4.7–35.8%, silt: 16.9–32.1% and clay 38.0–77.0% (figs. 4–5).

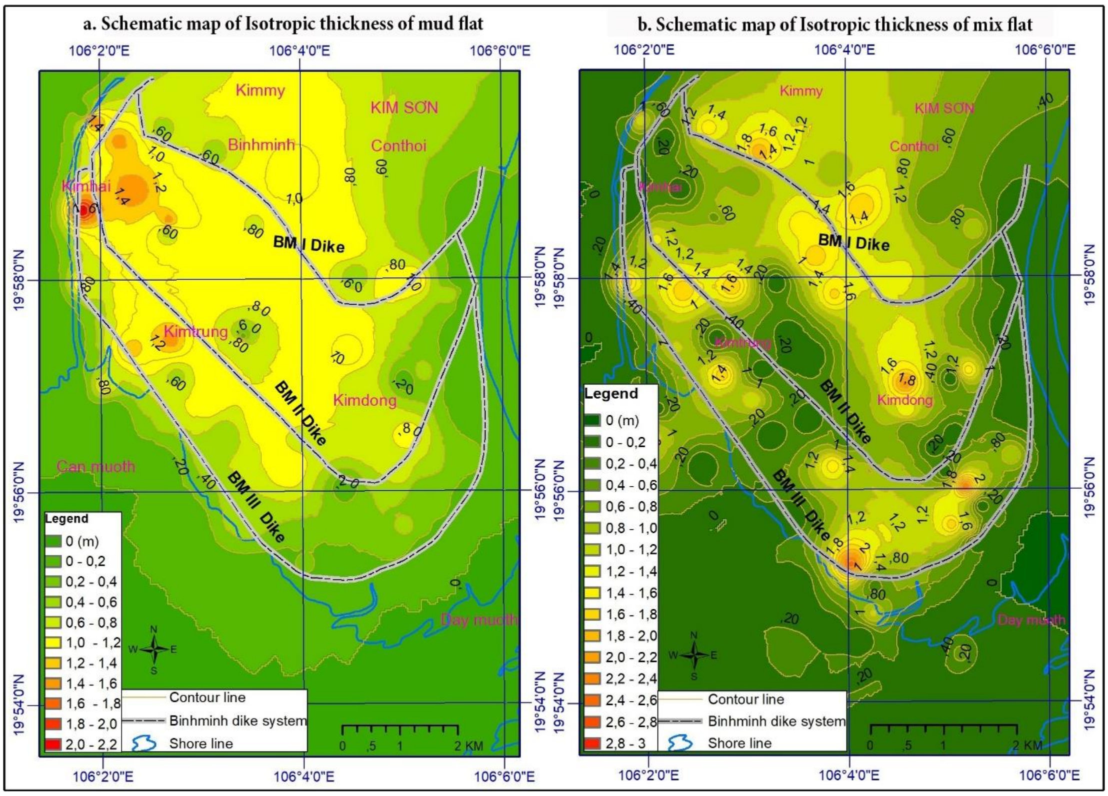

Figure 7. Thickness of tidal flat deposits in Kim Son - Ninh Binh

Figure 8. Mudflat deposits in LK.III-2 borehole (30–50 cm depth)

Morphological change at Kim Son tidal flats

Day estuary has the highest rate of variation in the Northern Delta. This is a favorable geographical position for the sedimentation of Red and Ma rivers. Over nearly 200 years, the Kim Son tidal flat has encroached on the sea more than 20 km. From 1921 up to now, Day estuary area encroached about 90–110 m/year, among the fastest accretion areas in the Red River Delta.

The data to analyze the fluctuation of Kim Son tidal flats from 1965 to 2020 include: Universal Transverse Mercator maps (UTM) at the scale of 1/50,000 in zone 48-Everest elliptical block published by the US Army Map Service (AMS) in 1965–1966, Landsat MSS satellite images (1973, 1975), Landsat TM satellite images (2001, 2003 and 2005), Landsat OLI satellite images (2013–2020), Spot-2 satellite images (1995), Sentinel-2A (2017–2020), and Sentinel-1 (2015 and 2017).

From the interpretation of remote sensing images, there are following changes over time:

(1) From 1965 to 1973, the best-developed tidal flats occur in the southwestern region (average accretion 400 m seaward). In the southeast of tidal flats, the coastline encroaching seaward is about 100 m. The total accretion area during this period is 417.6 ha (fig. 9).

(2) From 1973 to 1989, the southeastern part of Kim Son tidal flats encroached into the sea with a strong speed (about 1,500 m), with the strongest accretion of about 2,500 m. In the southwest of this tidal flat, the level of accretion is smaller (about 650 m). The total accretion area during this period is 1,146.0 ha.

(3) From 1989 to 1995, the largest accretion area is 1,750 m (about 295 m/year). This period is most favourable for mangrove forest development. The seaward encroachment of Kim Son tidal flats is quick. The total accretion area during this period is 110.0 ha.

(4) From 1995 to 2001, in the east and west of tidal flats, the accretion is very strong with a total accretion area of 695.3 ha.

(5) From 2001 to 2010, the accretion speed decreases compared with the previous periods. The strongest accretion area is Can estuary (500 m). The other accretion area is only 100–200 m. The total accretion area during this period is 217.1 ha.

(6) From 2010 to 2020, the accretion speed is greater than that in 2001–2010 period. The total accretion area during this period is 502.1 ha.

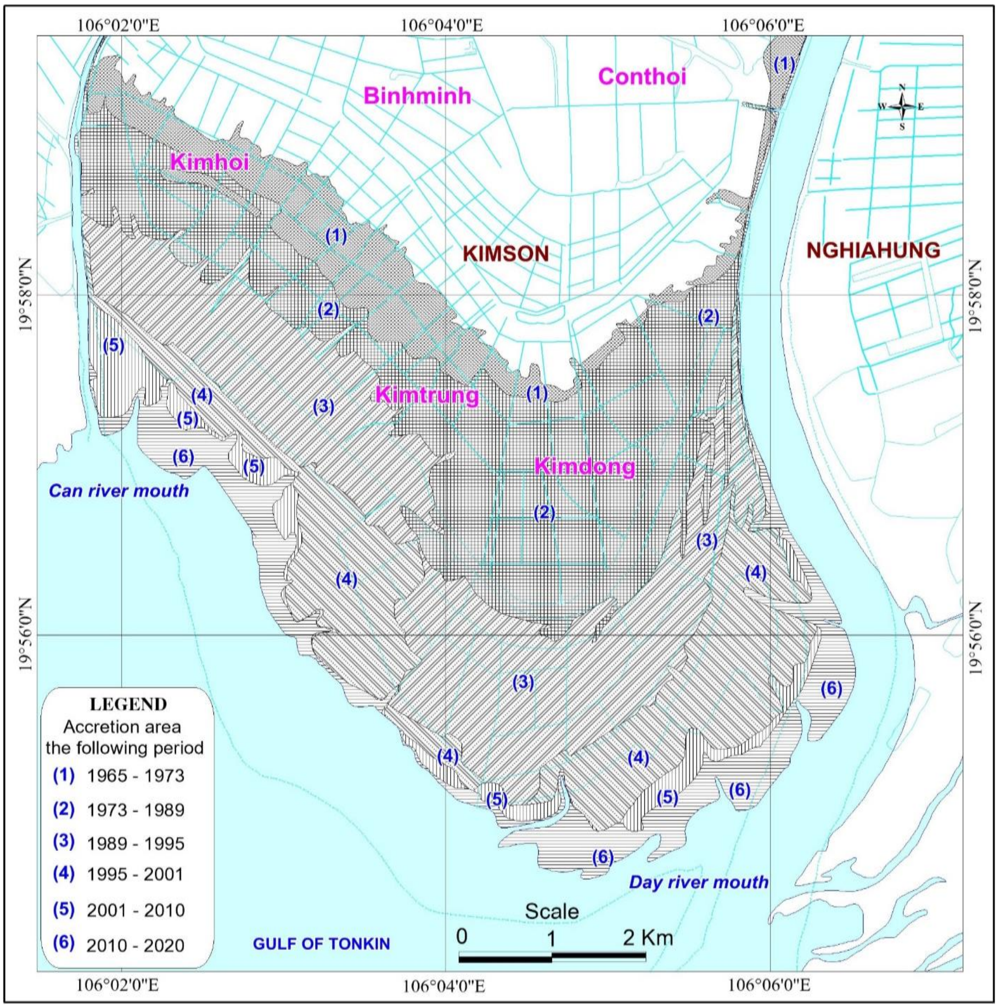

Figure 9. Changes of Kim Son - Ninh Binh tidal flat from 1965 to 2020

DISCUSSIONS

The sediments in tidal flat of Kim Son evolved in three stages, forming 1- sandy, 2- mixed and 3- muddy flats consecutively.

In the first stage, sediments, mainly composed of coarse-to-fine sands, were formed in the lower of the intertidal zone. The river-transported loads were deposited in strong dynamic environment forming sandbars in front of the estuary. These sandbars were destroyed and moved by waves and tides. Their materials were carried by tidal currents and re-deposited in the lower part of the intertidal zone in form of sandy tidal flats. The submerged sandbars in river mouth, identified clearly in the imageries of Landsat MSS dated 1973 and in Landsat TM5 dated 2005, the sandspits in TM dated 1989 (fig. 2) played a role both dissipating waves and supplying materials for the formation of tidal flats. The sandy tidal flats were distributed not only in the river mouth but also in the other coastal areas.

The stage forming mixed flats: The growth of sandy tidal flats weakened the dynamic of tidal currents, facilitating the deposition of finer materials in form of mixed flats characterized by the alternation of sand, silt, and clay. The sedimentation of coarser materials (sand) intercalated with the finers (silt, clay) (fig. 2) is due to the tidal activities. The spring tide with strong current favors the onshore transportation of coarse-grained sediments into tidal flats. Contrarily, neap tide is only convenient for transportation and deposition of fine-grained sediments (silt, clay). There is a similar changes caused by the alternation of dry and wet seasons.

The stage forming mud flats: The mud flats were formed as a result of sedimentation of the suspended loads transported by tidal creeks into the higher part of the intertidal zone, which was slightly impacted by tidal currents. The fairly quiet environment is favorable for the deposition of both suspended and biochemical sediments. Mangroves developed in this shallow water area, resulting in the presence roots, plant relicts and benthic organisms in sediments.

The formation and development of Kim Son tidal flat are the result of the Red river system carrying sandy mud with a wide flat. There is 32 billion cubic meters of water passing through Day estuary into the sea. In the rainy season, this sediment is dispersed 12 km seaward.

The development and fluctuation of the estuaries depend on the change in shape and direction of Day estuary. The Day estuary is fundamentally different compared to estuaries in the Red river Delta. This is a fast and continuous seaward accretion and stretch.

CONCLUSIONS

The sedimentary characteristics of Kim Son coastal plain are composed of tidal flat sediments and characterized by 3 tidal flat types. They formed according to the sequential evolution of tidal flats, i.e. sand flat, mixed flat, and mudflat.

Sand flats occupy the lower zones of tidal flats. In the Kim Son tidal flats, it is distributed at 1.8–2.0 m depth. The composition of sand flats consists of sand (43.1–87.0%), silt (10.0–35.8%) and clay (2.0–35.4%); sedimentological parameters: Median grain-size (Md) of 0.062–0.116, degree of sorting (So) of 1.298–2.814, skewness (Sk) of 0.381–0.840.

Mixed flats occur across the transition between sand flats and mudflats. Deposits typically consist of thinly interbedded wave- and current-ripple cross-laminated, very fine-grained sandstone and massive or parallel-laminated mudstone. The composition of the mixed flat consists of sand: 11.0–63.3%, silt: 16.9–52.7%; and clay 14.1–66.3%; sedimentological parameters: Md of 0.042–0.06, So of 3.013–5.586, Sk of 0.191–0.763.

Mudflats constitute the upper zone of the tidal flats. The mudflat deposits are dominated by parallel-laminated mudstone and intensely bioturbated by polychaetes, gastropods. The composition of grain is sand (4.7–35.8%), silt (16.9–32.1%) and clay (38.0–77.0%).

The Kim Son tidal flats have experienced 6 periods in more than 55 years (from 1965 to 2020): (1) 1965–1973 (with accretion area of 417.6 ha); (2) 1973–1989 (1,146.0 ha); (3) 1989–1995 (1,104.0 ha); (4) 1995–2001 (695.3 ha); (5) 2001–2010 (217.1 ha); and (6) 2010–2020 (502.1 ha). The total accretion area over the time is 4,081.2 ha.

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