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RESEARCH ARTICLE

# The important role of Turbidity Maximum Zone in sedimentary dynamic of estuarine mangrove swamp

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**Abstract** Sedimentation is a key process affecting wetland sustainability and carbon burial flux. In context of sea level rise, climate change and human activities, further understanding about the sedimentary dynamic in wetland is critical in predicting the landscape evolution or the change in carbon burial flux. In this study, based on the field hydrological observation in a mangrove system in the Nanliu River estuary, we found the net flux of suspended sediment to mangrove is 39–72 kg/m in tidal cycles with Turbidity Maximum Zone (TMZ) forming in surface layer and only is 9–18 kg/m in tidal cycles without TMZ. The higher net flux of suspended sediment to mangrove in tidal cycles with TMZ forming in surface layer is attributed to high SSC in rising tide and intense flocculation in mangrove. The significant discrepancy in sedimentation rate in the mangrove patches also can be explained by the probability of TMZ forming in the surface layer of estuary. In future, rapid sea level rising may lead to the change of TMZ pattern in estuary, which will result in non-negligible variation in sedimentation rate in wetlands. According to the present data of sedimentation rate in wetlands, the fragility of wetlands in river estuary may be miscalculated.

**Keywords** mangrove wetland, sedimentation, Turbidity Maximum Zone, Nanliu River

## 1 Introduction

The mangroves have many valuable functions such as biological habitat (Clough, 1998; Nagelkerken et al., 2008), carbon sequestration (Bouillon et al., 2008; Alongi, 2014) and coast protection (Kathiresan and Rajendran, 2005; Alongi, 2008). Sedimentation is a key process which affects the habitat sustainability and the organic carbon burial flux in mangroves. In context of sea level rise and climate change, sedimentary dynamic in mangroves is worthy of study to predict the landscape evolution of mangrove coast and the possible change in organic carbon burial flux in mangrove.

Given mangroves in estuary account a large proportion in the total mangrove area of this world. Many studies have been carried out to investigate the hydrology process (Mazda et al., 2005) and the suspended sediment flux at mangrove-river channel (tidal creek) interface (Bryce et al., 2003; Adame et al., 2010). As revealed by these studies, the current speed in mangrove is usually less than 10 cm/s in tidal cycles, which is caused by the intense friction from dense trunk and branch (Wolanski et al., 1998; Van Santen et al., 2007); the net flux of suspended sediment to mangrove within tidal cycles is thought to be positively correlated to tidal influx (Kitheka et al., 2003); flocculation can significantly enhance the fine particle sediment trapping in mangrove (Furukawa et al., 1997; Wolanski et al., 1998). In estuary, Turbidity Maximum Zone (TMZ) can form due to bottom re-suspension and horizontal transporting of suspended sediment (Festa and Hansen, 1978; Geyer, 1993), which will significantly enhance the suspended sediment concentration (SSC) level. However, the role of TMZ in the sedimentary dynamic of wetlands in estuary is still rarely discussed. The relationship between sedimentation in wetlands and TMZ pattern should be studied, which is critical in predicting the variation in sedimentation rate responding to sea level rise, climate change or human activities. In China, most of the mangroves locate in the estuaries of small rivers (average river discharge < 1000 $m^3$/s). Nanliu River is a typical small river in Guangxi province of China, large mangrove patches locate on the tidal flat off river mouths. From 1965 to 2020, the fluvial sediment discharge of Nanliu river declined by 80%, to study the erosion/acrretion of subaqueous delta responding to

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sediment supply decline, the hydrodynamic/sedimentation process on mangrove tidal flat in this area has attracted the attention of researchers (Long et al., 2022; Zhou et al., 2022). In this study, mainly based on the data from field hydrological observation, the TMZ pattern in Nanliu River estuary are analyzed and the net flux of sediment imported to mangrove within tidal cycles are calculated. The mechanism of TMZ adjusting sedimentation in mangrove is discussed. The possible change of sedimentation rate in wetlands in estuary responding to sea level rise is also discussed.

## 2 Study area and method

Locating in the Guangxi Province of China, Nanliu River flows into the Beibu Gulf of the South China Sea with an annual runoff of $2.1 \times 10^8 - 8.0 \times 10^8$ $m^3$. Controlled by a monsoon climate, the river runoff in flood season (April to September) usually accounts for about 80% of the total annual river runoff. Diurnal tide is dominant in this area, which average tidal range is 2.5 m. Nanliu River has three branches flowing into the Lianzhou Bay: Nanganjiang River, Muanjiang River and Dangjiang River. Off the river mouths of these branches, large mangrove patches which total area exceeds 600 ha (dominant plant is *Aegiceras corniculatum*) grow on the inner tidal flat.

To study the TMZ pattern in Nanliu River estuary and the net flux of suspended sediment (NFSS) imported to mangroves in tidal cycles, historical data of field hydrological observations was analyzed in this paper. At a site adjacent to river channel in a mangrove off the river mouth of Dangjiang River (Fig. 1), a MEDAS multi-parameter electromagnetic current meter with turbidity/conductivity/pressure sensors was used to measure the near bed (10 cm high above bed) hydrological parameters (pressure/water depth, current velocity, conductivity/salinity and turbidity) from 12th June to 26th June in 2014, the device sampling cycle was 20 min, an averaged value of five data was recorded at each sampling. With the sediment collected in mangrove, water samples with SSC of 0.2 g/L, 0.5 g/L, 0.8 g/L and 1.0 g/L were prepared in laboratory. The turbidity of water samples was measured by the multi-parameter electromagnetic current meter used in field observation. A function of turbidity to SSC was obtained by data fitting (Fig. 2). The data of turbidity recorded during field observation was then converted to SSC by this function. Moreover, in the channel of Dangjiang River (site 3) and Muanjiang River (site 2), a synchronous 24 h on-board hydrological

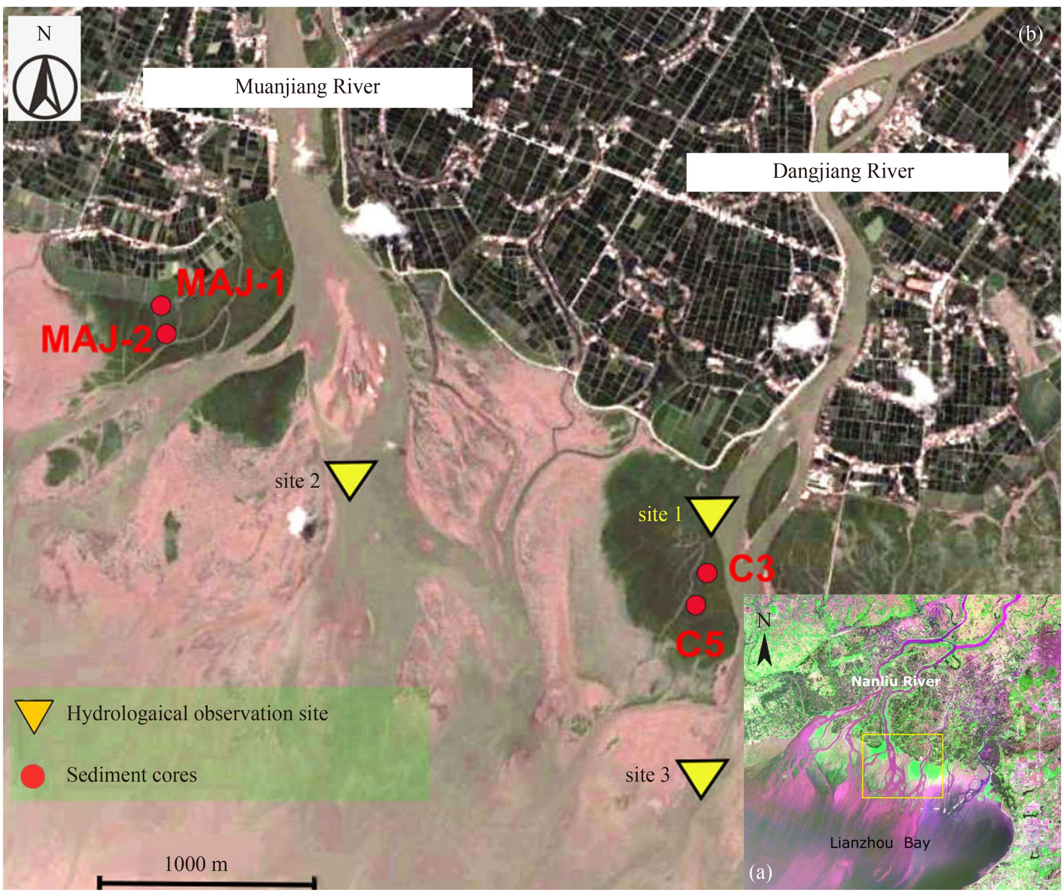


**Fig. 1** (a) Location of Nanliu River estuary and study area; (b) position of hydrology observation site and sediment cores.

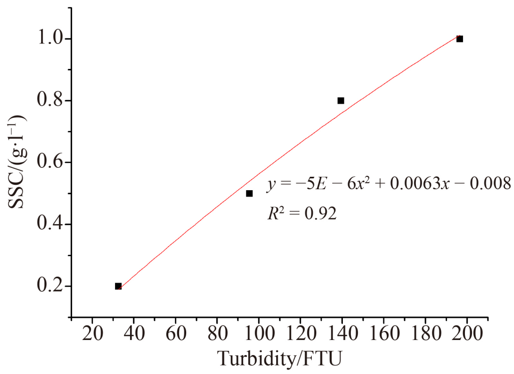


**Fig. 2** Fitting function of turbidity to SSC.

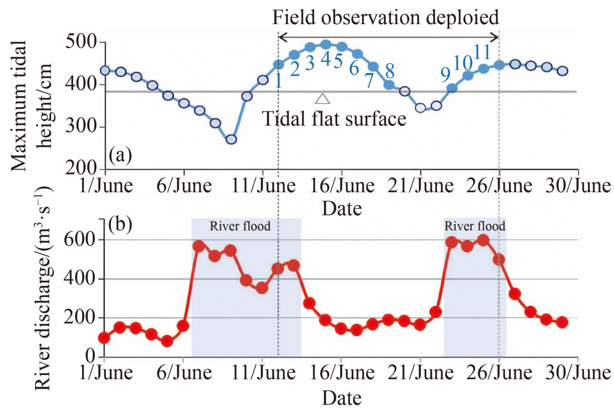


**Fig. 3** (a) Daily variation of maximum tide height; (b) Daily averaged river discharge during June, 2014.

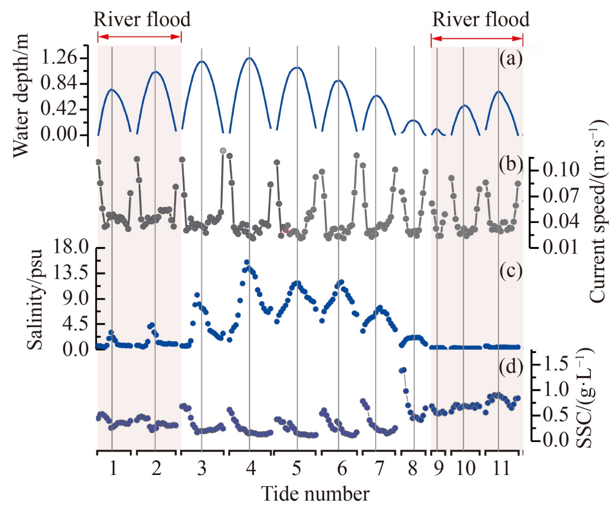


**Fig. 4** Time series of water depth (a), current speed (b), salinity (c) and SSC (d) during 11 tidal cycles at site1.

observation was carried out from 26th to 27th in December of 2012, during which current velocity measuring (with a direct reading current meter) and water sampling were deployed in the surface layer at a 1 h time interval. Then the salinity and SSC of water samples were measured in laboratory.

To study the long-term sedimentation rate in mangrove wetlands, the excess $^{210}$Pb radioactivity in four sediment cores (C3, C5, MAJ-1, MAJ-2) was studied, two of which (C3, C5) were collected in 2013 in a mangrove patch off the mouth of Dangjiang River and the others (MAJ-1, MAJ-2) were collected in 2016 in a mangrove patch off the mouth of Muanjiang River (Fig. 1(b)). Specific $^{210}$Pb/$^{226}$Ra radioactivity of sediment samples were measured with an isotope mass spectrometer (measuring error is ±9% − ±17%) in the State Key Laboratry of Lake Sciences of China, the excess $^{210}$Pb radioactivity of sediment samples was obtained by subtracting $^{226}$Ra radioactivity from $^{210}$Pb radioactivity.

## 3 Result

### 3.1 hydrology process in mangrove

At a site (site 1 in Fig. 1) in a mangrove patch off Dangjiang River mouth, time series of hydrological parameters covering 11 tidal cycles was recorded from 12th June to 26th June in 2014, during which two river flood events occurred (Fig. 3). As is shown in Fig. 4, except in the initial stage and final stage of tidal flat inundation, the near bed current speed in mangrove only is 0.02−0.05 m·s$^{-1}$. The current speed level in mangrove during this observation is similar with that reported in the mangroves around the world, which is very low due to the strong friction caused by trunk, branches and root. During river flood period (tide 1−tide 2, tide 9−tide 11), the salinity in mangrove was nearly zero throughout inundation time, indicating that the estuary is occupied by fresh water mass in tidal cycles. In the tidal cycles with normal river discharge (tide 3−tide 8), the salinity in mangrove was positively correlated to tidal height, indicating the salinity gradient in a well mixing estuary (Fig. 4(c)).

In the tidal cycles with normal river discharge, the maximum SSC was observed at the beginning of tidal flat inundation, then decreased with tide flooding (Fig. 4(d)). The SSC in ebb tide was significantly lower than that in flood tide, indicating most of the suspended sediment being trapped in mangrove during tidal flood. In the tidal cycles meeting river flood, the SSC was relatively stable, the reduction of SSC in ebb tide from that in flood tide is not significant, indicating most of suspended sediment did not deposit to bed in tidal cycles.

### 3.2 the TMZ pattern in Nanliu River estuary

Turbidity Maximum Zone (TMZ) can form in estuary due to bottom re-suspension and horizontal transporting of suspended sediment (Festa and Hansen, 1978; Geyer, 1993). In the good mixing estuary, the underlying water mass with high SSC can up-spring to surface layer, therefore TMZ will form in surface layer and the suspended sediment in TMZ can be transported into wetland by rising tide. A TMZ in surface layer can be identified in satellite images, for example, we can see a clear TMZ in the estuary of Dangjiang river in a satellite image which was took at 2011/8/28, while no obvious TMZ can be identified in the estuary of Muanjiang River (Fig. 5).

In the tidal cycles with normal river discharge (tide 3 to tide 8), the initial SSC in mangrove was very variable and usually was higher than that in the tidal cycles meeting river flood (Fig. 6(d)). The maximum initial SSC during this field investigation was observed at neap tide (tide 8) when both the river discharge and the tidal current speed was low. Obviously, the main factor controlling initial SSC is not the suspended sediment discharge or *in situ* re-suspension. It is most likely that the forming and moving of TMZ in the surface layer of estuary which resulted in

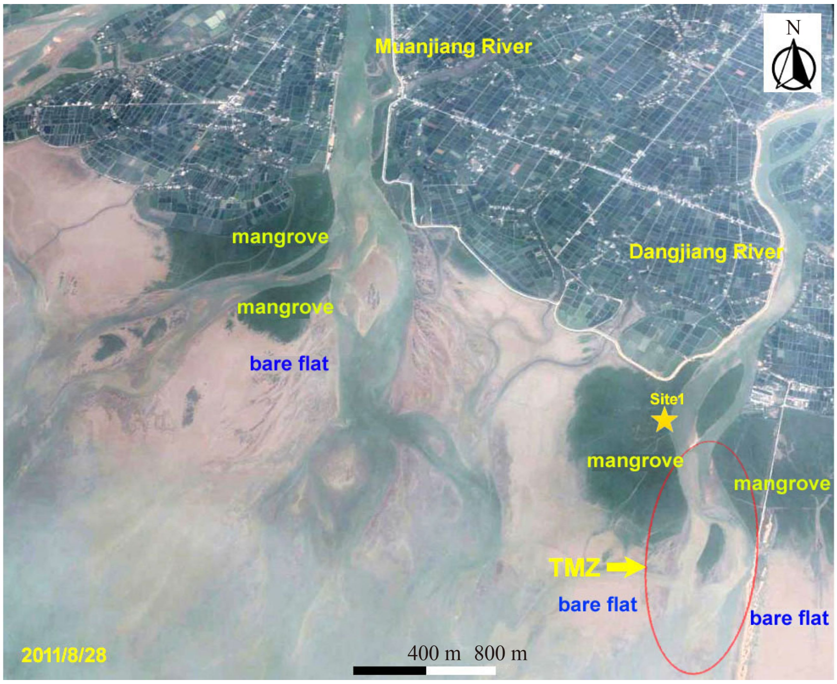


**Fig. 5** TMZ in the in surface layer of Dangjiang River identified in satellite image (from Google Earth).

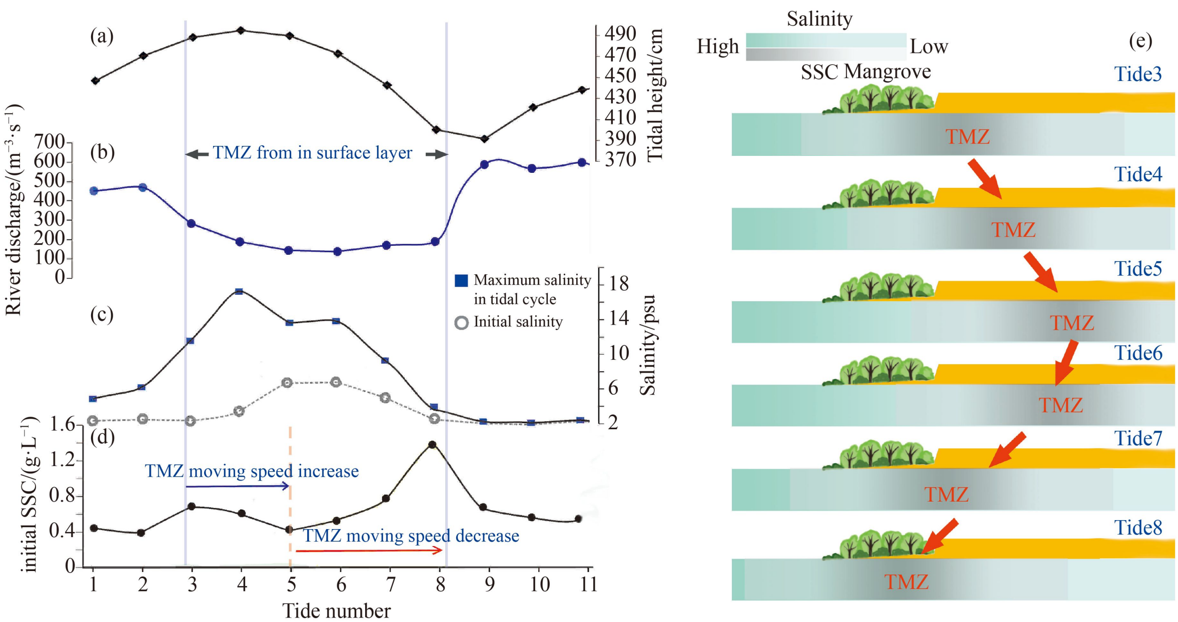


**Fig. 6** TMZ pattern analysis based on hydrological parameters in the estuary of Dangjiang branch (a–d) and (e) the inferred position of TMZ at the beginning of mangrove inundation.

this variation in initial SSC.

During river flood period (tide 1−tide 2, tide 9−tide 11), the estuary was occupied by fresh water mass all through tidal cycles and the variation in SSC was not significant. In the tidal cycles with normal river discharge (tide 3 to tide 8), the mixing in estuary is inferred to be good and TMZ should have formed in surface layer due to strong vertical diffusion of suspended sediment in bottom layer. TMZ will move landward with tidal influx during flood tide and its moving speed depend on the ratio of tidal influx to river discharge. For example, from tide 3 to tide 5, the tidal influx was basically stable and the river discharge kept reducing, so the moving speed of TMZ increased gradually. As a result, the position of TMZ is inferred to be further far away from mangrove at the beginning of tidal flat inundation (Fig. 6(e)), which led to a reduction in initial SSC from 0.72 $g\cdot L^{-1}$ to 0.55 $g\cdot L^{-1}$ (Fig. 6(c)). In contrast, the tidal influx kept reducing and the river discharge was basically constant from tide 5 to tide 8, so the moving speed of TMZ during tidal flood decreased. As a result, the position of TMZ was inferred to be closer to mangrove at the beginning of tidal flat inundation (Fig. 6(e)) and the initial SSC increased from 0.58 $g\cdot L^{-1}$ to 1.54 $g\cdot L^{-1}$ (Fig. 6(c)).

Nanliu River has four branches flowing into the Lianzhou Bay, among them Dangjiang River is the smallest one. Given the river discharge are very different for Dangjiang River and Muanjiang River, the probability of TMZ forming in the surface layer of estuaries shall be very different too. Compared with that of Muanjiang River, the probability of TMZ forming in the surface layer of Dangjiang River estuary is inferred to be higher due to its low river discharge. For example, in the satellite image covering study area (Fig. 5), we can see clear TMZ in the estuary of Dangjiang River, while no TMZ can be distinguished in the estuary of Muanjiang River. This supposition even can be supported by the field observation carried out simultaneously in the channels of Dangjiang River and Muanjiang River in dry season. As is shown in Figs. 7(a)−7(c), in the channel of Muanjiang River, the SSC in surface layer was negatively correlated to water depth within tidal cycle and the maximum SSC (35 mg/L) was observed at low tide when the current speed was still high (65 cm/s). The maximum SSC is most likely a result of *in situ* re-suspension and there was no signal of TMZ forming. In the channel of Dangjiang River, there are two peaks in the time series of surface SSC, both of which cannot be explained by *in situ* re-suspension. For example, the first SSC peak (43 $mg\cdot L^{-1}$) was observed in ebb tide when the water depth was still high and the second SSC peak (82 $mg\cdot L^{-1}$) was observed in the flood tide when the current speed (< 10 cm/s) was very low. These two SSC peaks in surface SSC is mostly likely caused by the moving of TMZ (in surface layer) in estuary.

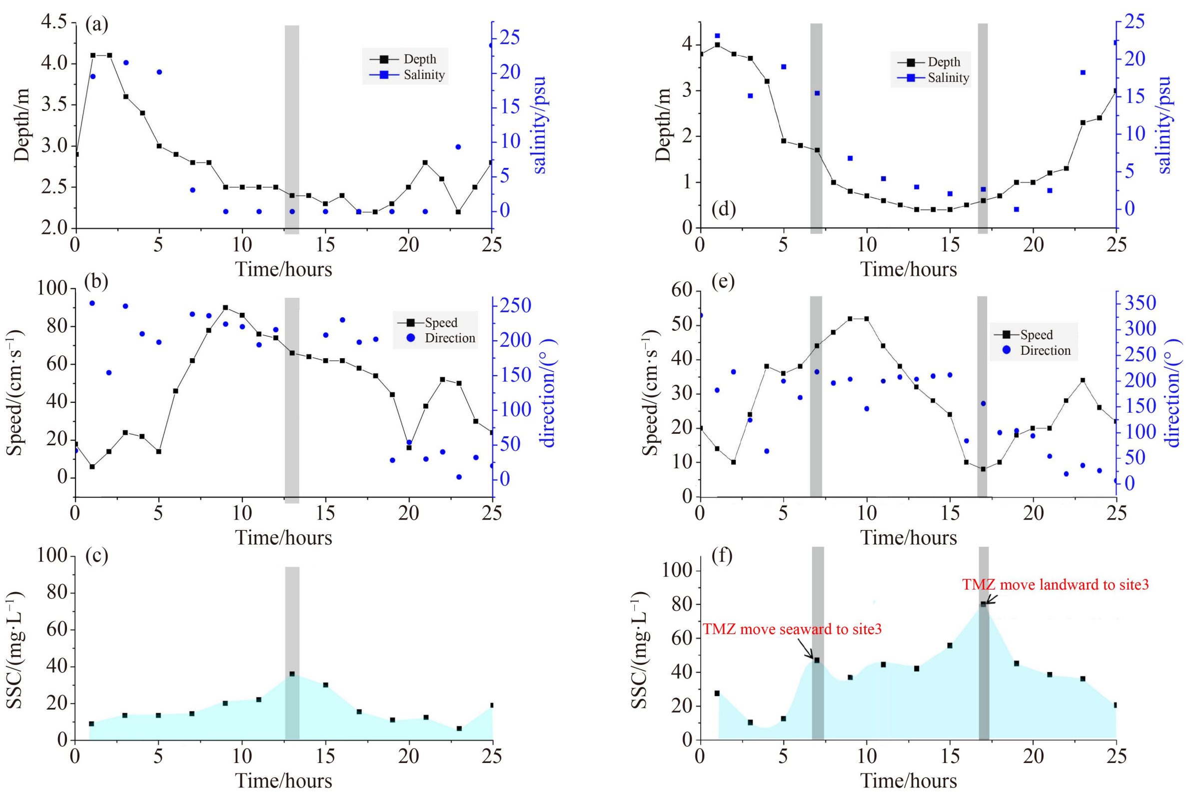


**Fig. 7** Time series of hydrological parameters in the surface layer at site 2 (a−c) and site 3 (d−f), which were observed during December 26th−27th in 2012.

### 3.3 Net suspended sediment flux to mangrove in tidal cycles

In mangrove, because the friction is mainly caused by dense trunks and branches, the current speed is nearly constant in depth. Moreover, the SSC level is the highest in the initial stage of mangrove inundation, when the water is still shallow (< 30 cm) and the variation in SSC with depth is not significant either. Thus, we can roughly calculate the suspended sediment flux by multiply the near bed current speed, SSC and water depth, then get the net suspended sediment flux (NSSF) to mangrove in tidal cycles. As shown in Fig. 8, the NSFF (39−72 kg·m$^{-1}$) in the tidal cycles (tide 3−tide 8) with TMZ forming in surface layer is significantly higher than that (9−18 kg·m$^{-1}$ ) in the tidal the cycles (tide1−tide 2, tide 9−tide 11) without TMZ forming. The promoting effect of TMZ to NSSF is especially significant during neap tide, when the moving speed of TMZ was low and the position of TMZ was still near river mouth (where mangrove locate) at the beginning of mangrove inundation. For example, the NSSF (42 kg·m$^{-1}$) of tide8 is 60% of that (70 kg·m$^{-1}$) of tide 4, while the tidal influx in tide 8 is only 30% of that in tide 4.

## 4 Discussion

According to this study, the NSSF to mangrove in the tidal cycles with TMZ forming in the surface layer of Nanliu River estuary was significantly higher than that in the tidal cycles without TMZ forming. This can be attributed to two aspects. First, TMZ in surface layer will enhance the SSC in rising tide flowing into mangrove, especially in the tidal cycles when the moving speed of TMZ was low and the position of TMZ is still near river mouth at the beginning of mangrove inundation. Secondly, TMZ in surface layer can form only in good mixing estuary, where flocculation is intense in brackish water and most of the suspended sediment in mangrove can deposit to bed within tidal cycles. In contrast, when the estuary is occupied by fresh water mass, most of suspended sediment transported into mangrove cannot deposit within tidal cycles due to weak flocculation. Therefore, the NFSS to mangrove in tidal cycles without TMZ forming in surface layer usually is much lower than that with TMZ forming in surface layer.

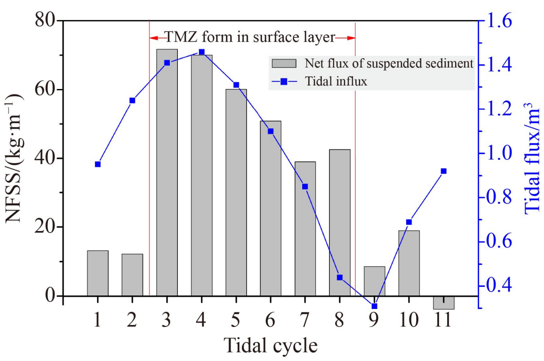


**Fig. 8** Net flux of suspended sediment imported to mangrove during tidal cycles at site 1.

Weather in wet season or in dry season, the probability of TMZ forming in the surface layer of Dangjiang River estuary is inferred to be higher than that in the Muanjiang River estuary due to its lower river discharge, this mean the NFSS to mangroves in tidal cycles in Dangjiang River estuary should be higher than that in the Muanjiang River estuary. As a result, the long-term sedimentation flux in the mangroves in Dangjiang River estuary should be higher than that in Muanjiang River estuary. This inference is supported by the sedimentation rate in mangroves determined by $^{210}$Pb dating. The sedimentation rate is 7.4−8.2 mm/yr in a mangrove patch in Dangjiang River estuary, while it is only 3.8−4.5 mm/yr in a mangrove patch in Muanjiang River estuary (Fig. 9). Around the world, the sedimentation rate in the mangroves in the estuaries of large rivers (average river discharge > 1000 m$^3$/s) usually is very low, for example, in the estuaries of in Amazon River and Ba lat River, the sedimentation rate in mangroves is less than 3 mm·yr$^{-1}$, while the sedimentation rate can exceed 10 mm·yr$^{-1}$ in the mangroves related to small rivers such as Nanliu River and Jiulong River (Table 1). Except inherent low SSC in river water, the poor mixing degree and low probability of TMZ forming in the surface layer of estuary may be the important reason of low sedimentation rate in mangroves in the estuaries of these large rivers.

According to this study, when TMZ forms in the surface layer of estuary, the SSC level in rising tide is mainly affected by the moving speed of TMZ, which is positively correlated to the ratio of tidal influx (TI) to river discharge (RD) in estuary. For example, in the estuary of Dangjiang River, with the increase of TI/RD ratio from tide 3 to tide 5, the TMZ went landward through river mouth (where mangroves locate) faster during tidal flood (Fig. 6(e)). As a result, the distance of TMZ core region away from river mouth increased and the mean SSC level in rising tide to mangrove declined. This indicate the enhancing effect of TMZ to sedimentation in mangrove will decline with the TI/ RD ratio in this estuary. In future, if the tidal influx increases due to sea level rise or human activity (for example, sand mining in river channel) in the estuary of small rivers like Nanliu River, the sedimentation rate in mangroves will decrease significantly. In contrast, for the rivers with high discharge, tidal influx increase in estuary caused by sea level rise or human activities will enhance the mixing degree in estuary and the probability of TMZ forming in surface layer. Thus, the sedimentation rate in mangroves will increase.

In the studies about mangrove sustainability, the

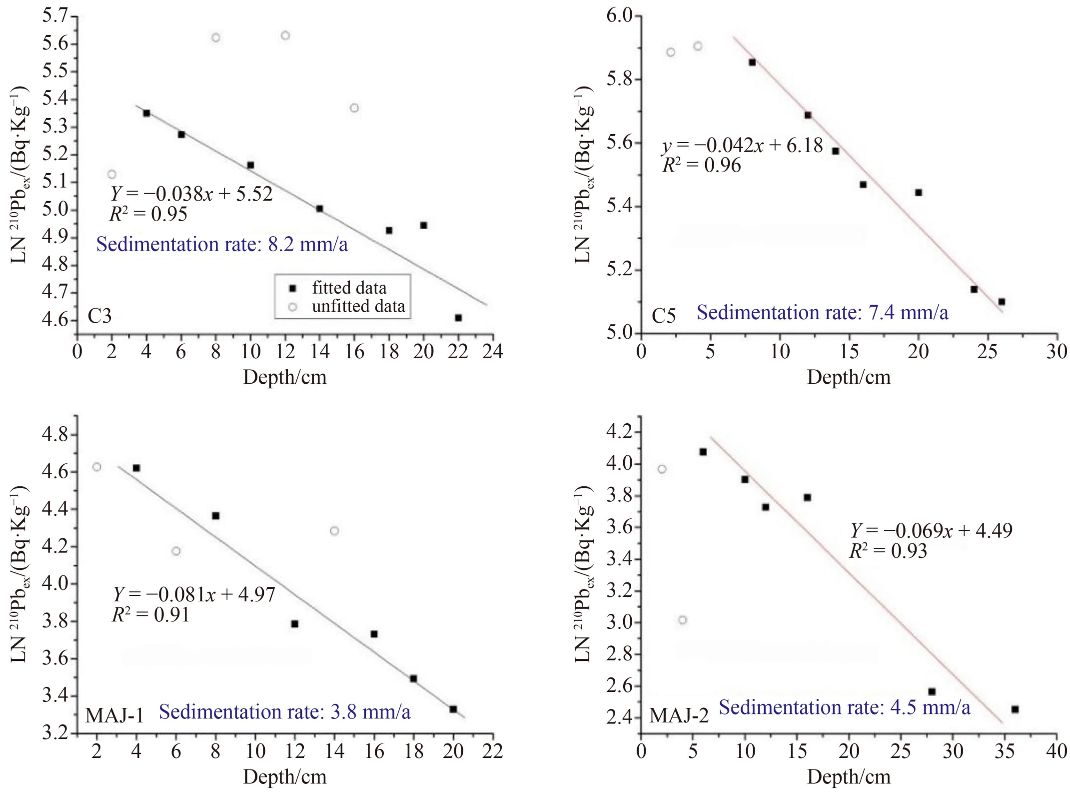


**Fig. 9** Depth profile of excess $^{210}Pb$ specific radioactivity in sediment cores.

**Table 1** The sedimentation rate in mangroves in different river estuary

| Estuary | River discharge/($m^3 \cdot s^{-1}$) | Average Tidal range/m | Sedimentation rate/($mm \cdot yr^{-1}$) |
|---|---|---|---|
| Jiulong River, China | 446 | 2.2 | 6–20 (Alongi et al., 2005) |
| Nanliu River,China | 244 | 2.4 | 3.8–15 |
| Amazon River, Brazil | 219000 | 3.1 | 0.8–2.6 (França et al., 2012) |
| Ba Lat River, vienam | About 3000 | 1.3 | 1.8–2.4 (Van Santen et al., 2007) |

present sedimentation rate is usually used to assess the threaten of sea level rise to mangroves (Lovelock et al., 2015; Nerem et al., 2018). However, according to this study, the change in sedimentation rate with sea level rise should not be neglected. In the estuary of small rivers, a decrease in sedimentation rate in mangroves may occur due to TMZ moving speed enhancing caused by tidal influx increase caused by rapid sea level rise. In contrast, the sedimentation rate in the mangroves in large river estuaries may increase due to the increase in probability of TMZ forming in the surface layer of estuary with rapid sea level rising. This mean the mangroves in small river estuaries may be more fragile than we predicting based on their present sedimentation rate, while the mangroves in large river estuaries is more sustainable than we predicting. Therefore, more studies including field observation and numerical simulation should be carried out to reveal the relationship between sedimentation rate, TMZ pattern and sea level rise.

## 5 Conclusions

Based on the field hydrological observation in Nanliu River estuary, we found that TMZ plays an important role in the sedimentary dynamic of mangrove wetlands. During tidal cycles with TMZ forming in the surface layer of estuary, the NFSS to mangrove is significantly higher than that in the tidal cycles without TMZ. The enhancing effect of TMZ to NFSS is attributed to high SSC in rising tide and intense flocculation in mangrove. The discrepancy in the sedimentation rate in mangrove patches in Nanliu River estuary also can be well explained by the probability of TMZ forming in surface layer. In future, if the sea level rise is rapid enough, the sedimentation rate in mangrove will change with the variation of TMZ pattern. According to the present data of sedimentation rate, the fragility of mangrove wetlands in estuary may be miscalculated.

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**Competing interests** The authors declare that they have no competing interests.

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