Impact of water and sediment discharges on subaqueous delta evolution in Yangtze Estuary from 1950 to 2010

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Abstract: In order to determine how the subaqueous delta evolution depends on the water and sediment processes in the Yangtze Estuary, the amounts of water and sediment discharged into the estuary were studied. The results show that, during the period from 1950 to 2010, there was no significant change in the annual water discharge, and the multi-annual mean water discharge increased in dry seasons and decreased in flood seasons. However, the annual sediment discharge and the multi-annual mean sediment discharge in flood and dry seasons took on a decreasing trend, and the intra-annual distribution of water and sediment discharges tended to be uniform. The evolution process from deposition to erosion occurred at the −10 m and −20 m isobaths of the subaqueous delta. The enhanced annual water and sediment discharges had a silting-up effect on the delta, and the effect of sediment was greater than that of water. Based on data analysis, empirical curves were built to present the relationships between the water and sediment discharges over a year or in dry and flood seasons and the erosion/deposition rates in typical regions of the subaqueous delta, whose evolution followed the pattern of silting in flood seasons and scouring in dry seasons. Notably, the Three Gorges Dam has changed the distribution processes of water and sediment discharges, and the dam’s regulating and reserving functions can benefit the subaqueous delta deposition when the annual water and sediment discharges are not affected.

Key words: water discharge; sediment discharge; seasonal change; delta; Yangtze Estuary

1 Introduction

Over the past hundred years, sediment discharge of rivers all over the world has sharply declined because dams or water transfer projects have been implemented along rivers, resulting in erosion of subaqueous deltas, especially deltas in estuary regions (Trenhaile 1997). Changes of sediment discharge not only affect the deposition rate, but also alter the features of silting and scouring (Syvitski et al. 2005). Many submerged deltas have been deposited more slowly or eroded after a decrease of seaward sediment discharge all around the world, such as along the Nile River (Frihy et al. 2003), the Colorado River (Carriquiry et al. 2001), and the
Yellow River (Xu 2008). During the deltaic evolution, contradictions exist between rivers and oceans, and rivers usually dominate the process (Ren 1989). Chinese scholars (Yang et al. 2003a; Li et al. 2004; Li et al. 2007; Wang et al. 2010; Gao 2010; Yang et al. 2011) have investigated the relationship between the evolution of the Yangtze subaqueous delta and the sediment discharge, and established empirical curves of the relation between the sediment discharge and the evolution of typical regions of subaqueous deltas. However, the relation between delta evolution and seaward water discharge has not been analyzed. The water cycle mechanism in the delta region of the American Colorado River has changed due to the reduction of water discharge, resulting in a different mechanism of deposition in the estuary delta region (Fanos 1995). Meanwhile, the decreased sediment blocked the extension of the Colorado delta. In the Mississippi River Basin, the sediment transport was reduced by 40% from 1963 to 1989 due to the extremely high usage of river water, which was considered the major reason for the deltaic erosion in estuary areas (Qian et al. 1989). Yang et al. (2003b) showed that it was not rigorous in theory to use only water discharge, sediment discharge, or sediment concentration as a single index to determine the critical value of water or sediment discharge for maintaining the balance of deposition and erosion in delta regions.

Generally, when the increase rate of water discharge is higher than that of the sediment discharge, the sediment concentration will decrease. Hence, the variations of basin water and sediment discharges may trigger significant delta changes. In the Yangtze Estuary, flooding plays a riverbed-rebuilding role. When the water discharge is larger than 60,000 m$^3$/s, the water level in the middle and lower reaches of the Yangtze River is significantly enhanced. Meanwhile, the silting and scouring variations in the river channel are significant. When the flood discharge exceeds 70,000 m$^3$/s, new river branches and erosion appear frequently (Gong and Yun 2002). Especially in 1954 and 1998, two heavy floods greatly influenced the erosion and deposition of the subaqueous delta in the river mouth. Studies on the evolution of the Yellow River delta revealed that the water and sediment discharges not only drove the delta-rebuilding but also determined the deltaic evolution trend (Xu 2002). Thus, when studying the deltaic evolution, the sediment discharge should not be the only considered factor. Instead, the collective influence of both water and sediment discharges should receive full attention. In recent years, with gradually increasing human activities in the Yangtze River Basin, their effects on water discharge, sediment discharge, and the intra-annual distribution processes of water and sediment discharges have already appeared (Yang et al. 2004; Chen et al. 2005; Dai et al. 2008; Dai et al. 2009; Li et al. 2011), and the water discharge and sediment discharge, as well as their intra-annual distribution processes, have also had a direct effect on the subaqueous delta development. Overall, it is necessary to establish the relationship between the subaqueous delta evolution and the water and sediment discharges in the Yangtze Estuary, and, in particular, to determine how the distributions of water and sediment discharges over different seasons affects the subaqueous delta evolution.
In this study, we investigated the variation trends of the annual water and sediment discharges, the amounts of water and sediment in dry and flood seasons, and the distribution processes of water and sediment discharges. Based on the results, the relationships between the areal erosion/deposition rates in typical regions of the subaqueous delta and the water and sediment discharges over a year or during dry and flood seasons were studied. This study demonstrated the relationship between the subaqueous delta evolution in the Yangtze Estuary and the decisive elements.

2 Study area and methods

2.1 Study area

The Yangtze River Basin originates in the Tanggula Mountains, and has a full length of 6300 km, covering an area of $1.84 \times 10^6$ km$^2$. The Datong Hydrographic Station is the most downstream large-scale hydrological station along the main stream of the Yangtze River, where the amounts of water and sediment represent the water and sediment processes of the Yangtze River. The geomorphologic patterns of the Yangtze Estuary include three-order bifurcations and four outlets into the sea. The Yangtze Estuary is divided into the South Branch and the North Branch by the Chongming Island, and the South Branch is divided into the South Channel and the North Channel by the Changxing Island. The South Channel is again divided into the South Passage and the North Passage by the Jiuduansha Shoal. Fig. 1 shows the study area for this project, which is 68 km from the south to the north, covering the affected region of the $-10$ m and $-20$ m isobaths of the subaqueous delta in the Yangtze Estuary.

![Fig. 1 Sketch of study area in Yangtze Estuary](image)

2.2 Sources of information and description

Map information from 1958 to 1989 was obtained through a digitized electronic chart (on
a scale of 1:15 000). Map information from 2002 to 2009 came from the measured topographic data provided by the Yangtze River Waterway Bureau and Shanghai Estuarine and Coastal Science Research Center. All data from different departments and organizations using different measurement approaches were conformed to the same conditions through comparison and examination.

According to the analysis of sediment diffusion effects in the Yangtze Estuary by Yun (2004), the outer boundary of diffusion range of muddy water is between the −20 m isobath and −30 m isobath. Both the −10 m and −20 m isobaths are within the affected area of muddy water diffusion. Therefore, they are mainly controlled by the water and sediment discharges.

For a subaqueous delta, the variations of the erosion/deposition rate include the change of the areal erosion/deposition rate and the change of the volumetric erosion/deposition rate (Gao 2010). In this study, the areal erosion/deposition rates at the −10 m and −20 m isobaths were investigated. In this way, delta evolution could be better reflected, and formulas were established to demonstrate the relation between the areal erosion/deposition rate and the water and sediment discharges over a year or during dry and flood seasons.

3 Change processes of seaward water and sediment amounts in Yangtze River Basin

3.1 Variation rules of annual water and sediment discharges

The annual water and sediment discharges in the Yangtze River Basin are high. From 1950 to 2010, the multi-annual mean water discharge reached 8\(970 \times 10^8\) m\(^3\)/year. From 1951 to 2010, the multi-annual mean sediment discharge was 3.88\(\times 10^8\) t/year, and the sediment concentration was 0.43 kg/m\(^3\). As shown in Fig. 2(a), the annual water discharge has not changed significantly from 1950 to 2010. In the 1990s, the annual water discharge slightly increased, while from 2000 to 2010, the annual water discharge decreased somewhat, whereas the annual sediment discharge was sharply reduced in general. The stepwise reduction occurred in years such as 1968, 1985, and 2002. Especially in recent years, the decrease of the annual sediment discharge presents a more dramatic trend. Compared with the multi-annual sediment discharge from 1951 to 1968, the multi-annual sediment discharge from 2003 to 2010 showed a reduction of 3.37\(\times 10^8\) t/year, with a reduction rate of 68.92%. Notably, the decrease of annual sediment discharge occurred along with the sharp sediment reduction at the Yichang and Hankou stations located in the middle and lower reaches of the Yangtze River (Yang et al. 2011). As shown in Fig. 2(b), the suspended sediment concentration has declined since 1985. If the amount of water does not change too much, the flow is less capable of transporting sediment and the riverbed sediment is suspended to compensate for the deficiency, which triggers a scouring trend in the estuary subaqueous delta.
3.2 Variation characteristics of water and sediment discharges in flood and dry seasons

The riverbed evolution in the middle and lower reaches of the Yangtze River follows the basic pattern of silting in flood seasons, and scouring in dry seasons. Hence, it is critical to determine how the variations of annual water and sediment discharges in flood and dry seasons affect the evolution of the subaqueous delta.

Fig. 3(a) shows the variation of multi-annual mean water discharge in flood and dry seasons. It can be seen that the multi-annual mean water discharge showed a reduction trend in flood seasons in most years except the 1990s, with the smallest amount in the 2000s. The multi-annual mean water discharge in dry seasons from 1950 to 1979 was smaller than that from 1980 to 2009, implicating the slight increase in dry seasons. Moreover, the percentage of multi-annual mean water discharge took on a downward reduction in flood seasons and an upward increase in dry seasons, which suggests that the amount of water distributed in flood and dry seasons tends to be uniform. As shown in Fig.3(b), the maximum multi-annual mean sediment discharge in flood seasons was in the 1960s, and thereafter it gradually declined. In the 2000s, the multi-annual mean sediment discharge was only $1.57 \times 10^8$ t/year in flood seasons. In particular, the annual sediment discharge was only $0.84 \times 10^8$ t/year in 2006. Similarly, the multi-annual mean sediment discharge tended to decline in dry seasons, which means that the reduction of annual sediment discharge occurred along with the sediment decrease in both flood and dry seasons. The percentage of multi-annual mean sediment discharge tended to decrease in flood seasons, and increase in dry seasons. The intra-annual distributions of sediment and water discharges tended to be uniform.

Overall, the multi-annual mean water and sediment discharges decreased in flood seasons, but in dry seasons the multi-annual mean water discharge showed a rising trend, and the multi-annual mean sediment discharge decreased. The percentages of multi-annual mean water and sediment discharges decreased in flood seasons, and increased in dry seasons.
3.3 Variation characteristics of large and small water discharges in flood and dry seasons

The riverbed-rebuilding discharge in the Yangtze Estuary is 60 400 m³/s. When the actual discharge is larger than that value, distinct erosion-deposition variations are observed in the estuary, which causes the replacement of main branches. For example, the flood in 1954 played a critical role in the development of the North Passage. It changed the top and shallow regions of mouth bars, and the erosion and deposition fluctuations were from 0.2 to 0.7 m, which resulted in changes in the shoal-cutting and split ratios, influencing the estuary waterway (Yun 2004). As shown in Fig. 4, the number of days with a discharge larger than 50 000 m³/s at the Datong Hydrographic Station has shown a decreasing trend since 1950, and the number of days with a discharge smaller than 15 000 m³/s has also tended to decrease. The results indicate that the medium amount of discharge increased in percentage, and the intra-annual distribution of water discharge was more uniform.

4 Relation between water and sediment processes in Yangtze River Basin and evolution of typical regions in subaqueous delta

Variations of the areal erosion/deposition rates at typical isobaths of the subaqueous delta were examined. If the silting area between the same isobaths in different years is larger than the scouring area, the region near the isobath appears as deposition. In contrast, if the silting area is smaller than the scouring area, the region near the isobath appears as erosion. The areal erosion/deposition rate at an isobath in the subaqueous delta can be expressed as
\[ V = \frac{A_d - A_e}{T} \]  

where \( V \) is the areal deposition/erosion rate at the deltaic isobath (\( \text{km}^2/\text{year} \)), \( A_d \) and \( A_e \) are the areas of deposition and erosion (\( \text{km}^2 \)), respectively, and \( T \) is the time interval (year).

### 4.1 Evolution law of typical regions in subaqueous delta

Fig. 5 shows variations of the \(-10 \text{ m}\) and \(-20 \text{ m}\) isobaths in the Yangtze Estuary from 1958 to 2009, and the areal erosion/deposition rates at the two isobaths are listed in Table 1.

During the period from 1958 to 1985, the multi-annual mean sediment discharge was \(4.56 \times 10^8 \text{ t/ year}\), and the regions near the \(-10 \text{ m}\) and \(-20 \text{ m}\) isobaths showed a deposition trend. From 1985 to 1989, the multi-annual mean sediment discharge was \(3.66 \times 10^8 \text{ t/ year}\), the area above the \(-10 \text{ m}\) isobath slightly decreased, indicating that the region near the \(-10 \text{ m}\) isobath appear as erosion, but the region near the \(-20 \text{ m}\) isobath appeared as deposition. From 1989 to 2002, the multi-annual mean sediment discharge was \(3.42 \times 10^8 \text{ t/ year}\), and the area above the \(-10 \text{ m}\) isobath showed an increasing trend. As mentioned in section 3, the annual water
Table 1 Multi-annual mean sediment discharge and areal erosion/deposition rates at typical isobaths of subaqueous delta

<table>
<thead>
<tr>
<th>Period</th>
<th>−10 m isobath</th>
<th>−20 m isobath</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Multi-annual</td>
<td>Multi-annual</td>
</tr>
<tr>
<td></td>
<td>mean sediment</td>
<td>mean sediment</td>
</tr>
<tr>
<td></td>
<td>discharge (10^8 t/year)</td>
<td>discharge (10^8 t/year)</td>
</tr>
<tr>
<td></td>
<td>Areal erosion/deposition</td>
<td>Areal erosion/deposition</td>
</tr>
<tr>
<td></td>
<td>rate (km²/year)</td>
<td>rate (km²/year)</td>
</tr>
<tr>
<td>1958-1985</td>
<td>4.56</td>
<td>4.56</td>
</tr>
<tr>
<td></td>
<td>7.67</td>
<td>6.15</td>
</tr>
<tr>
<td>1985-1989</td>
<td>3.66</td>
<td>3.66</td>
</tr>
<tr>
<td></td>
<td>−3.11</td>
<td>5.03</td>
</tr>
<tr>
<td>1989-2002</td>
<td>3.42</td>
<td>3.18</td>
</tr>
<tr>
<td></td>
<td>6.37</td>
<td>1.75</td>
</tr>
<tr>
<td>2002-2004</td>
<td>1.77</td>
<td>3.18</td>
</tr>
<tr>
<td></td>
<td>−27.61</td>
<td>1.75</td>
</tr>
<tr>
<td>2004-2007</td>
<td>1.46</td>
<td>1.46</td>
</tr>
<tr>
<td></td>
<td>−23.97</td>
<td>−10.51</td>
</tr>
<tr>
<td>2007-2009</td>
<td>1.20</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>−40.84</td>
<td>−23.44</td>
</tr>
</tbody>
</table>

Note: The positive value denotes deposition and the negative value denotes erosion.

discharge during this period was significantly larger than in other periods. Although the annual sediment discharge was smaller than that in previous periods, the annual water discharge increase caused a deposition trend in the subaqueous delta. From 1989 to 2004, the area above the −20 m isobath maintained an upward trend and the region near the −20 m isobath appeared as deposition, caused by the same factor as that mentioned above for the deposition in the region near the −10 m isobath during this period. From 2002 to 2004, the area above the −10 m isobath tended to decrease, and an erosional retreat occurred. The area above the −10 m isobath decreased continually from 2002 to 2009, and the erosional retreat was significant. Similarly, the area above the −20 m isobath showed a reduction from 2004 to 2009, and the corresponding annual sediment discharge ranged from 0.84 × 10^8 to 2.77 × 10^8 t/year. Thus, the annual sediment discharge from the Yangtze River into the estuary subaqueous delta was significantly reduced compared with that in previous periods. In 2006, the sediment discharge was only 0.84 × 10^8 t/year. Meanwhile, the areas above the −10 m and −20 m isobaths decreased with the most serious observed retreat. The areal erosion rate from 2007 to 2009 increased compared with that from 2004 to 2007 because of the variations of seaward sediment and water discharges caused by the Three Gorges Dam.

To sum up, a process from deposition to erosion occurred at the −10 m and −20 m isobaths of the subaqueous delta along with a reduction of sediment discharge. A continuous erosional retreat has occurred in the subaqueous delta of the Yangtze Estuary since 2002.

In the future, if the sediment entering the estuary remains at a low level for a long time, it will cause serious erosion of the subaqueous delta. Hence, the estuarine wetland protection and the safety of ports and cities will be extremely threatened.

4.2 Relationship between annual water and sediment discharges and erosion/deposition rate in typical regions

As discussed above, when the sediment discharge decreased, the subaqueous delta would gradually shift from a stated of deposition to erosion. As Fig. 6 shows, there is a linear relation between the erosion/deposition rate at the isobath of the subaqueous delta and annual water
discharge (Fig. 6(a)) and annual sediment discharge (Fig. 6(b)). When the annual water and sediment discharges decrease, the subaqueous delta in the Yangtze Estuary shifts from a state of deposition to reduced deposition or even to erosional retreat in the end. An analysis method of multiple regressions was used to establish the relation curves between the area erosion/deposition rates at typical isobaths of the subaqueous delta and the annual water and sediment discharges. The formulas are shown below:

\[ V_1 = -110.83 + \frac{7.74}{1000}Q + 11.70S \quad R^2 = 0.92 \]  
\[ V_2 = -34.95 + \frac{1.30}{1000}Q + 7.77S \quad R^2 = 0.86 \]

where \( V_1 \) and \( V_2 \) are the area deposition/erosion rates at the \(-10\) m and \(-20\) m isobaths (km\(^2\)/year), respectively; \( Q \) is the annual water discharge (10\(^8\) m\(^3\)/year); \( S \) is the annual sediment discharge (10\(^8\) t/year); \( R^2 \) is the coefficient of determination; and the coefficient 1000 converts the units of water and sediment discharges to the same order of magnitude. Fitting curves are obtained under the confidence coefficient \( \alpha = 0.1 \).

According to Eqs. (2) and (3), the deltaic evolution was jointly affected by the annual water and sediment discharges. Based on the coefficients of \( Q \) and \( S \) in Eqs. (2) and (3), the contributions of annual sediment discharge and annual water discharge to the areal erosion/deposition rate at the \(-10\) m isobath were 61.88% and 38.12%, respectively, while 61.01% of the sediment contribution and 38.99% of the water contribution were observed for the areal erosion/deposition rate at the \(-20\) m isobath. Hence, annual sediment discharge variations have a more significant effect than annual water discharge variations on the evolution of the subaqueous delta. However, the effect of annual water discharge variations on the deltaic evolution should not be ignored.

4.3 Relationship between water or sediment variation process and evolution of typical deltaic regions

The water and sediment discharges showed better correlation with the areal
erosion/deposition rate at the deltaic isobaths in flood seasons than in dry seasons (Fig. 7). Whether or not the sediment discharge increased in flood seasons or in dry seasons, the delta always shift from a state of erosion to deposition. Based on the erosion/deposition rates at different subaqueous deltaic isobaths, and water and sediment discharges in flood and dry seasons, curves demonstrating the relationship between the water/sediment variation process and the evolution of the subaqueous delta were built, and the specific fitting formulas are shown in Table 2. Compared with the curves shown in Fig. 6, these curves are more accurate because the water and sediment discharges were examined in both flood seasons and dry seasons. The coefficients of $Q_F$ and $S_F$ in the formulas in Table 2 were positive and the coefficients of $Q_D$ and $S_D$ were negative, suggesting that the water and sediment discharges promoted deposition of the subaqueous delta in flood seasons, and erosion in dry seasons. Accordingly, the delta showed a deposition trend in flood seasons and an erosion trend in dry seasons, which is consistent with the basic pattern for the evolution of the middle and lower reaches of the Yangtze River: silting in flood seasons and scouring in dry seasons.

![Fig. 7](image)

**Fig. 7** Relation between subaqueous delta evolution and variation processes of water and sediment discharges in different seasons

**Table 2** Relation curves of areal erosion/deposition rates at typical isobaths and water/sediment discharge in different seasons

<table>
<thead>
<tr>
<th>Single factor</th>
<th>Isobath (m)</th>
<th>Empirical curve</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water discharge</td>
<td>-10</td>
<td>$V_i = 41.84Q_i/1000 - 41.84Q_o/1000 - 128.17$</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>-20</td>
<td>$V_i = 27.68Q_i/1000 - 63.22Q_o/1000 - 4.81$</td>
<td>0.95</td>
</tr>
<tr>
<td>Sediment discharge</td>
<td>-10</td>
<td>$V_i = 25.09S_i/1000 - 111.46S_o - 30.52$</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>-20</td>
<td>$V_i = 22.85S_i/1000 - 148.62S_o - 3.56$</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Note: $Q_i$ and $Q_o$ are the water discharges in flood seasons and dry seasons ($10^8$ m$^3$/year), respectively; $S_i$ and $S_o$ are the sediment discharges in flood seasons and dry seasons ($10^8$ t/year), respectively; and fitting curves were obtained with the confidence coefficient $\alpha = 0.1$.

The Three Gorges Dam has been used for water storage since 2003, maintaining the water and sediment discharges in the Yangtze River Basin at a certain level. The dam showed a lesser effect on the annual water discharge, while the water distributions in flood and dry seasons were changed somewhat. Meanwhile, the annual sediment discharge showed a
downward trend, and the distributions of sediment discharge in flood and dry seasons were also changed. According to the coefficients of $Q_F$, $Q_D$, $S_F$, and $S_D$ in the formulas in Table 2, the absolute values of the coefficients of $Q_D$ and $S_D$ were larger than those of $Q_F$ and $S_F$, respectively, which suggests that if the reduced amount of water and sediment in flood seasons was emptied in dry seasons, the deltaic deposition area in a dry season would be larger than the erosion area caused by the water and sediment discharge reduction in a flood season. Because of the different distributions of the water and sediment discharges in flood and dry seasons throughout a year, the delta tended to show deposition development. Assuming that the water and sediment discharges reduced by the Three Gorges Dam in a flood season was all emptied in the dry season, the reduced deposition value of the subaqueous delta in the flood season should be smaller than the increased value in the dry season, indicating a deposition trend of the deltaic evolution. Therefore, the Three Gorges project has changed the distribution processes of water and sediment discharges, and its regulation function can benefit the subaqueous delta deposition, while the annual water and sediment discharges in the basin are not affected.

### 4.4 Relationship between water and sediment variation processes and evolution of typical deltaic regions

Comprehensively considering the effects of the water and sediment discharges in flood and dry seasons, we established curves to describe the relationships between the areal erosion/deposition rates at different isobaths and the water and sediment discharges. Fitting curves were obtained under the confidence coefficient $\alpha = 0.1$. The formulas for the curves of $-10$ m and $-20$ m isobaths are as follows:

$$V_1 = \frac{8.93Q_F}{1000} + \frac{12.64Q_D}{1000} + 27.11S_F - 155.40S_D - 104.89 \quad R^2 = 0.94$$  \hspace{1cm} (4)

$$V_2 = \frac{42.13Q_F}{1000} - \frac{96.66Q_D}{1000} + 3.12S_F - 84.42S_D + 19.11 \quad R^2 = 0.98$$  \hspace{1cm} (5)

According to these formulas, it can be found that comprehensive consideration of the effects of the water and sediment variation processes on the deltaic evolution can reflect the variations of areal erosion/deposition rates at the $-10$ m and $-20$ m isobaths in the subaqueous delta much more accurately. Lou (2005) analyzed the subaqueous delta variations from 1997 to 2000, and the reported data were used to test our fitting formulas. From 1997 to 2000, the water discharges in flood and dry seasons were $8.427 \times 10^8$ m$^3$/year and $2.989 \times 10^8$ m$^3$/year, respectively, and the sediment discharges were $3.20 \times 10^8$ t/year and $0.39 \times 10^8$ t/year, respectively. According to our calculation, the $-10$ m and $-20$ m isobaths should have an areal erosion/deposition rate of $34.29$ km$^2$/year and $63.09$ km$^2$/year, respectively, consistent with the values obtained by Lou (2005) of $36.43$ km$^2$/year and $69.63$ km$^2$/year, respectively.
5 Conclusions

(1) The annual water discharge showed no obvious trend from 1950 to 2010, while the annual sediment discharge showed a stepwise decrease. The multi-annual mean water discharge decreased in flood seasons and increased in dry seasons. The multi-annual mean sediment discharge decreased in dry seasons and flood seasons. The percentages of multi-annual mean water and sediment discharges decreased in flood seasons, and increased in dry seasons.

(2) An evolution process from deposition to erosion occurred at the −10 m and −20 m isobaths of the subaqueous delta, and empirical curves were established to present the relationships between the annual water and sediment discharges and the areal erosion/deposition rates in typical regions of the subaqueous delta. The annual sediment discharge variation had a greater effect on the evolution of the subaqueous delta than the annual water discharge variation.

(3) Empirical curves were established to describe the relationships between the deltaic areal erosion/deposition rates in typical regions of the subaqueous delta and the water and sediment discharges in flood and dry seasons, and the evolution of the subaqueous delta was found to follow the pattern of silting in flood seasons and scouring in dry seasons. Although the Three Gorges Dam has changed the distribution processes of water and sediment discharges throughout a year, the regulation and reservation functions of the dam can benefit the deltaic deposition when the annual water and sediment discharges are not affected.

The evolution of the estuary delta is controlled by the water and sediment factors in the basin. However, the ocean dynamics vary continuously, and their effects on the deltaic evolution are still unclear. In the future, we will pay more attention to the effect of ocean factors on the deltaic evolution and the corresponding empirical relationship.

References


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