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Impact of dams on Yangtze River sediment supply to the sea and delta intertidal wetland response

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[1] On the basis of estimates of sediment accumulation in reservoirs, the impact of 50,000 dams on sediment supply and intertidal wetland response in the Yangtze River catchment is examined. The total storage capacity of reservoirs is 200×10^9 m^3, or 22% of the Yangtze annual runoff. The sediment accumulation rate in reservoirs has increased from ~0 in 1950 to >850×10^6 t/yr in 2003. Although sediment yield has increased with broader soil erosion in the river basin, the total riverine sediment discharge rate shows a strong decreasing trend from the late 1960s to 2003, likely due to dam construction. Consequently, the total growth rate of intertidal wetlands at the delta front has decreased dramatically. A significant relationship exists between intertidal wetland growth rate and riverine sediment supply that suggests riverine sediment supply is a governing factor in the interannual to interdecadal evolution of delta wetlands. Regression analysis of intertidal wetland growth rate and sediment supply shows that intertidal wetlands at the delta front degrades when the riverine sediment discharge rate reaches a threshold level of <263×10^6 t/yr. Owing to the construction of the Three Gorges Dam and other new dams, the sediment discharge rate of the Yangtze River will most likely decrease to below 150×10^6 t/yr in the coming decades. Therefore unless current management policies are adjusted, drastic recession of Yangtze River delta intertidal wetlands can be expected to occur.

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1. Introduction

[2] Many deltas worldwide are retreating due to decreases in sediment supply from river [*Trenhaile*, 1997]. The Colorado River in the USA once supplied more than 150×10^6 t/yr of sediment to the Gulf of California. River diversions and sediment trapping by dams have prevented a great portion of sediment from reaching the Colorado Delta, which has resulted in coastal recession [*Carriquiry et al.*, 2001]. Sediment discharge from the Nile River in Egypt was once between 100 and 124×10^6 t/yr. At present, almost no net annual sediment load is delivered to the Nile delta due to the construction of dams, especially the Aswan High Dam that was put into operation in 1964 [*Stanley and Warne*, 1998; *Frihy et al.*, 2003]. Accordingly, recession of the promontories formed at the mouths of two active tributaries of the Nile has been very rapid [*Fanos*, 1995; *Wiegel*, 1996]. After the construction of the Ribarroja-Mequinenza dam complex in northern Spain, about 96% of Ebro River sediment was trapped in the reservoir and the progradation of the delta as a whole ceased [*Sánchez-Arcilla et al.*, 1998]. The Yellow River (Huanghe) in China, once the world's largest in sediment discharge [*Milliman and Meade*, 1983], is now providing less than 100×10^6 t/yr of sediment to the sea due to dam construction and water withdrawals. The Yellow River delta as a whole is degrading [*Yang et al.*, 2004].

[3] The progradation/recession of intertidal wetlands at the delta front is usually a representative of delta evolution. Intertidal wetlands are important ecosystems that provide nursery habitats for fish, dissipate water energy, filter contaminants, provide resting areas for migratory birds, support biodiversity, offer opportunities for recreation, hunting, and fishing, and provide intrinsic values such as aesthetics and education [*Goodwin et al.*, 2001]. The Yangtze delta intertidal wetlands have been listed as one of the world's

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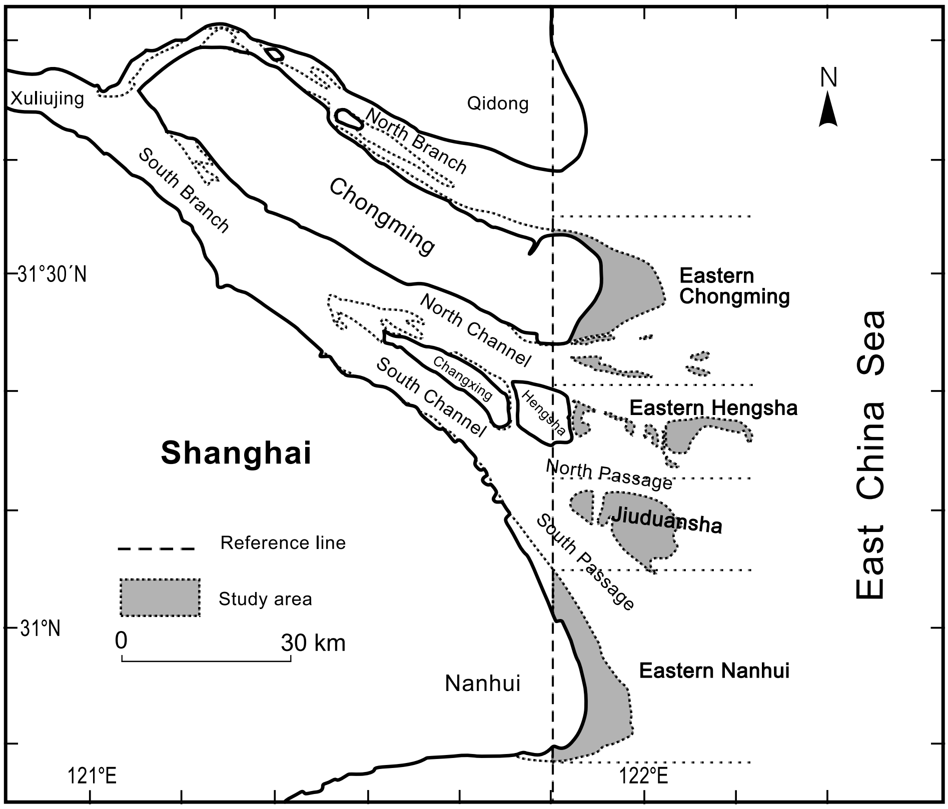

Figure 1. Yangtze River mouth. The study area is the region of intertidal wetlands east of the reference line and is divided into four sectors.

important wetland ecosystems [*Lu*, 1997; *Wang and Qian*, 1988; *Maff et al.*, 2000; *State Forestry Administration*, 2000; *Zhao et al.*, 2003]. Two intertidal wetlands, eastern Chongming and Jiuduansha (Figure 1), have been designated as natural reserves by the Chinese government.

[4] The rapid progradation of the Yangtze delta has made it possible for Shanghai, currently the largest city in China, to pursue a policy of reclaiming land from intertidal wetlands. Nearly 2/3 of the Shanghai land area was obtained in this way during the last 2000 years, with 1/5 of it obtained in the last half century [*Yang*, 1999]. Shanghai plans to further reclaim 767 km^2 of intertidal wetlands in this and the coming decade [*SCWAPDI et al.*, 2002]. This is more than the current total area of intertidal wetlands. This plan is based upon an assumption that the intertidal wetlands will continue to prograde at a high rate. Understanding and predicting the evolutionary trend of intertidal wetlands is therefore critical in appraising the rationality of current government policies. Although a preliminary study shows that the progradation of the subaqueous delta has greatly reduced in response to the decrease in riverine sediment supply [*Yang et al.*, 2003], there has been little research on the response of the intertidal wetlands.

[5] This study examines the influence of catchment dams on Yangtze River sediment supply and on the delta advancement. Intertidal wetlands at the delta front (Figure 1) covering a total area of 411 km^2 were selected to study delta response. Documented sediment accumulation rates, recorded riverine sediment transport data, and measured changes in delta intertidal wetland coverage are used to (1) calculate the amount of sediment trapped in reservoirs, (2) examine the influence of dam trapping on riverine sediment load, (3) establish a statistical relationship between riverine sediment discharge and growth rate of intertidal wetlands at the delta front, (4) evaluate the thresholds of riverine sediment discharge with regard to the stability of intertidal wetlands, and (5) predict the trend in riverine sediment supply and delta wetland evolution in the coming decades in relation to the Three Gorges Dam (TGD) and other new dams.

2. Physical Setting

[6] The Yangtze River is one of the largest rivers in the world. It originates on the Qinghai-Tibet Plateau at 5100 m elevation and extends 6300 km eastward to the East China Sea [*Chen and Li*, 1979]. The catchment covers a total area of 1,808,500 km^2 and, at present, is home to a population of more than 400 million. The upper reaches of the river end at Yichang, 30 km downstream of TGD, in Hubei Province, China. Along the middle and lower reaches of the river, many lakes connect to the main stream. Lake Dongting, one of the largest freshwater lakes in China, plays an important role in regulating the riverine sediment load [*Yang et al.*, 2003].

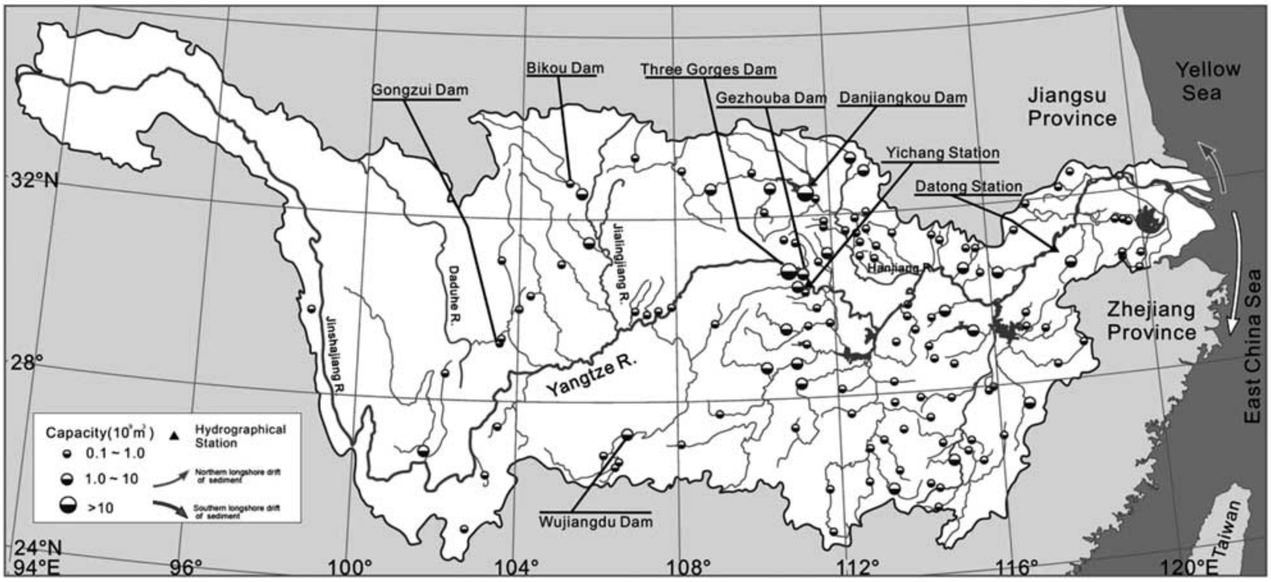

Figure 2. Yangtze River basin showing the distribution of large reservoirs (>10^8 m^3 in storage capacity) and hydrographical gauging stations at Yichang and Datong.

[7] During the dry season, the tidal effects reach 640 km upriver to Datong, which is located downstream of 94% of the catchment area. Datong is the location of a major gauging station for riverine water and sediment flux measurements (Figure 2). Upstream of Datong, the river can be expected not to be influenced by tides. Downstream of Datong, however, the river level fluctuates in response to tides. The range of fluctuations increases from Datong to the delta front. In the first 400 km downstream of Datong, although the flow speed tidally varies, the flow direction is always seaward and the water is always fresh. Further downstream, both the flow speed and the flow direction tidally vary [*Chen et al.*, 1988a, 1988b].

[8] The Yangtze River mouth below Xuliujing is bifurcated, with a width of 90 km at the outer limit (Figure 1). Since the 1950s, nearly all riverine discharge has flowed via the South Branch system [*Chen et al.*, 1985]. As a result, outlets of the Southern Branch are the major depocenters for Yangtze River sediment. Mean and maximum tidal ranges are 2.7 m and >5.0 m, respectively. Wave activity is generally moderate, with a mean wave height of 1.0 m at the outer mouth [*Yang*, 1999]. The inner continental shelf on which the delta is built is less than a 1‰ gradient. Longshore currents off the estuary carry a great quantity of riverine sediment southward to the Zhejiang Province coast in winter and northward to the Jiangsu Province coast in summer [*Yang et al.*, 2000] (Figure 2). During the past 2000–3000 years, the delta coastline has prograded at a rate of 10–20 m/yr, and intertidal wetlands as a whole have grown at a rate of about 5 km^2/yr [*Yang et al.*, 2001a]. Deltaic progradation rate has accelerated in recent centuries (Figure 3) probably because of intensification of deforestation in the catchment area and the resultant increase in riverine sediment supply to the sea.

[9] In this study, "delta front" means the portion of the delta exposed to the East China Sea. Intertidal wetlands at the delta front are several kilometers in width under normal natural conditions, but their actual width depends on intensity of reclamation. The lower portion of local intertidal wetlands is permanently bare whereas the higher portion is covered by *Scirpus* and reeds during their growing seasons [*Yang*, 1998].

3. Materials and Methods

[10] Data on soil erosion rates, sediment yield, sediment deposition in reservoirs, lakes, and channels, and riverine water and sediment discharge were collected from the institutions of Yangtze River Water Conservancy Committee. This data set was used to examine the impact of dam trapping on sediment supply to the sea. Delta bathymetric maps from 1971 to 1998 were collected to examine temporal variations in the growth rate of intertidal wetlands. These maps were surveyed by the China Maritime Survey Bureau using depth sounding (inner space 449 thermal depth sounder recorder with frequency of 23.5 kHz). The accuracy of the surveys was 0.1 m. The map scale is 1:120,000, with a contour interval of 1 m. Since 1999, several large-scale engineering projects have been carried out in the study area that likely interfere with the response of intertidal wetlands to riverine sediment supply [*Du et al.*, 2005]. In order to filter out the influences of these structures, only bathymetric maps before 1999 were utilized to examine intertidal wetland growth rates. On these maps, the theoretically lowest tidal lines (0 m contours which are about 2 m below the mean sea level) on eastern Chongming, eastern Hengsha, Jiuduansha and eastern Nanhui were shown, but elevation data was absent for most of the intertidal areas due to logistic problems. Variation in the 0 m contour line reflects net progradation/recession of the intertidal wetlands.

[11] In the study area, the movement of the 0 m contour is typically variable due to the complexity of local hydrodynamics and geomorphology as well as to sediment supply and deposition. The 0 m contour advances in some areas while it retreats in others (Figure 4). Therefore temporal variation in the 0 m contour line (m/yr) alone is an

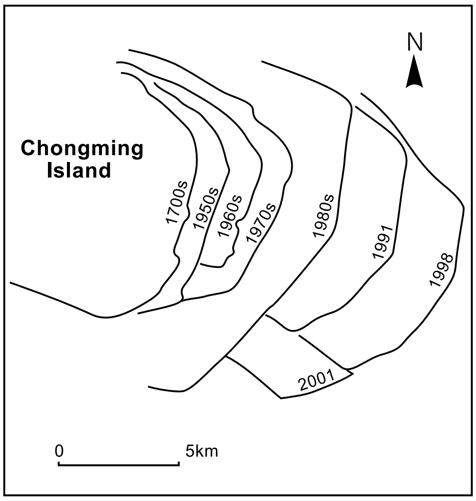

Figure 3. Advancement of coastline (seawall) on the eastern Chongming Island (the data source for the coastlines from the 1700s to the 1960s is *Chen* [1988], and the data source for the coastlines from the 1970s to 2001 is personal field surveys using GPS).

ineffective means of quantifying the rate of shoreline movement. The growth rate of intertidal wetlands was thereby estimated by calculating the change in total wetland area over time expressed in units of km^2/yr. In large deltas such as the Yellow River delta and the Yangtze River delta, this method is easier and more accurate than the calculation of progradation rate in unit of m/yr [*Xu*, 2003].

[12] Bathymetric maps of four intertidal wetlands (eastern Chongming, eastern Hengsha, Jiuduansha and eastern Nanhui) (Figure 1) over different periods (1971, 1975, 1979, 1983, 1987, 1991, 1995 and 1998) were scanned into jpeg format. These images were digitized using MapInfo software in order to allow for the calculation of intertidal wetland area.

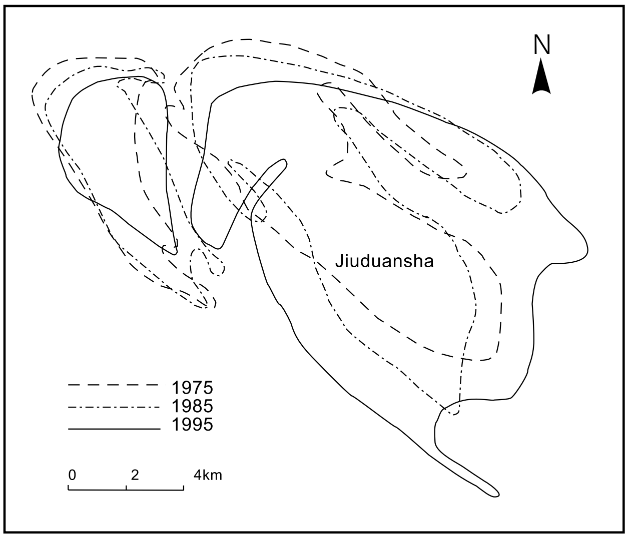

Figure 4. Shift of the 0 m contour (theoretically lowest tidal line) on Jiuduansha intertidal wetland (data sources are bathymetric maps from the China Maritime Survey Bureau).

[13] On Jiuduansha and eastern Hengsha, the intertidal wetland is encircled by the 0 m contour, and the temporal change in intertidal area reflects progradation or recession. On eastern Chongming and eastern Nanhui, however, the intertidal wetland exists between the 0 m contour and the seawall. Because parts of these intertidal wetlands were reclaimed between 1971 and 1998, the temporal change in intertidal area reflects both progradation/recession and reclamation. In order to filter the interference of reclamation, a reference line (the 121°50′E longitude) was introduced. The reference line was located on the landside of the seawall in 1971 and was not influenced by reclamation that occurred between 1971 and 1998. Because the reference line was static, the temporal change in area between the 0 m contour and the reference line reflects the shift of the 0 m contour or progradation or recession.

[14] Change in area was estimated between each set of measurements taken in 1971, 1975, 1979, 1983, 1987, 1991, 1995 and 1998. For example, the area of eastern Chongming intertidal wetland in 1971 was subtracted from that in 1975 to give a difference of 44.4 km^2. This suggests that the intertidal wetland grew by 44.4 km^2 from 1971 to 1975, with a growth rate of 11.1 km^2/yr (Table 1). The total growth rate shown in Table 1 is the sum of the rates in the four sectors.

[15] Area was calculated using MapInfo software by fitting a series of polygons to a given area then summing the areas of the polygons to calculate total area. In order to estimate the error associated with polygon method, a 15 cm diameter circle with an area of 176.7 cm^2 was used. The circle was approximated as a polygon whose sides intersect the arc of the circle and are equally parted by the point of intersection. In this way, the area of the polygon can be compared to the actual area of the circle to estimate the error associated with the software (polygon) method. The area of the polygon was measured between 176 and 178 cm^2, an error of <1%. Therefore the software based polygon method was taken as a suitable approach for calculating the area of intertidal wetlands.

[16] Regression analysis was performed using Microsoft Excel and SPSS 12.0 software. The 3 year running average was an average of the previous year, the current year and the next year.

4. Results and Discussion

4.1. Dam Constructions in the River Basin

[17] Since 1950, many dams have been constructed in the Yangtze River catchment. The total storage capacity of reservoirs in the upper reaches of the river in 1950 was

Table 1. Growth Rates on the Intertidal Wetlands at the Delta Front of Yangtze River[a]

Period	Eastern Chongming	Eastern Hengsha	Jiuduansha	Eastern Nanhui	Total
1971–1975	11.1	1.1	1.4	−1.8	11.8
1975–1979	8.8	0.8	2.2	−1	10.8
1979–1983	6.6	0.5	2.4	−0.3	9.2
1983–1987	4.5	0.4	2.7	0.5	8.1
1987–1991	1.9	0.2	2.9	1.2	6.2
1991–1995	−0.5	0	3.1	2	4.6
1995–1998	−2.5	−0.1	3.3	2.6	3.3
Totals, km^2	122.1	11.7	70.7	10.2	215

[a] Rates are in km^2/yr.

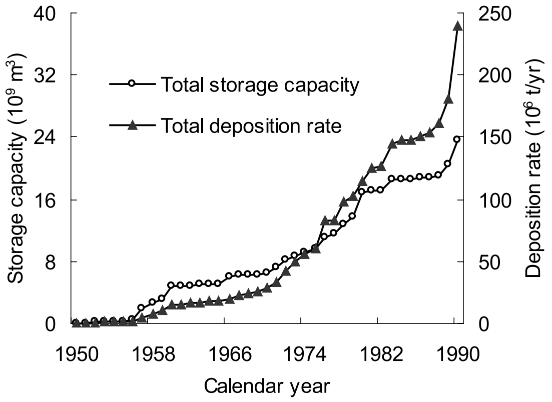

Figure 5. Total storage capacity and deposition rate in reservoirs in the upper reaches of the Yangtze River (data source is the Yangtze River Water Conservancy Committee).

only 0.06 × 10^9 m^3. By 1990 it had increased to 23 × 10^9 m^3 due to dam construction (Figure 5). By 1995, 45,628 dams had been constructed in the river basin with a total storage capacity of 142 × 10^9 m^3. Sixty-four percent of this capacity was attributed to 119 large-scale reservoirs (>0.1 × 10^9 m^3 storage capacity) [*CCYRA*, 1999]. By the end of 2002, 143 large-scale reservoirs had been constructed (Figure 2) with a total storage capacity of 115 × 10^9 m^3 [*CCYRA*, 2003]. This represents a 26.5% increase from 1995 to 2002. In this period, seven other large reservoirs were also in construction [*CCYRA*, 2003], including TGD. The number of dams in the watersheds is about 50,000 at present. According to the storage capacity ratio of large-scale reservoirs to total number of reservoirs in 1995, the total storage capacity of reservoirs in the Yangtze catchment reached about 180 × 10^9 m^3 by the end of 2002. The TGD reservoir began to impound water in June of 2003. By the end of 2003, the associated TGD reservoir water level rose to 140 m above sea level. When the dam construction is finished in 2009, the reservoir water level will be at 175 m above sea level. The storage capacity of TGD Reservoir is expected to be 17.15 × 10^9, 22.8 × 10^9 and 39.3 × 10^9 m^3 when the water level is at 145, 155, and 175 m above sea level, respectively (Society of Water Conservancy of China, unpublished data, 2001).

[18] The relationship between the data on storage capacity and water level of reservoir shown above yields a storage capacity of 14.63 × 10^9 m^3 at 140 m above sea level. Taking into account other dams constructed after 2002, the cumulative storage capacity of reservoirs in the catchment is 200 × 10^9 m^3 at present. This represents about 22% of the annual water discharge from Yangtze River to the sea. This storage to discharge ratio exceeds the world average of 20% (available at http://www.seaweb.org/background/book/dams.html). According to *CCYRA* [2002], 95% of the total storage capacity is derived from reservoirs that are located in the drainage area upstream of Datong.

4.2. Deposition in Reservoirs

[19] Dams efficiently trap riverine sediment. Trapping efficiency of reservoirs can be expressed as the impounded ratio of sediment (IRS), or the percent of sediment deposited in a given reservoir versus the total sediment input to the reservoir. With regard to TGD, 124 × 10^6 t, or 60%, of the total sediment load from upstream, was deposited in the TGD reservoir from June to December 2003 (available at http://www.irtces.org/nishagb_2003.asp).

[20] The Danjiangkou Reservoir in Hanjiang River, a tributary in the middle reaches of Yangtze, was built in 1959. It was the largest reservoir in terms of storage capacity on the river catchment before TGD. From 1960 to 1994, 1.41 × 10^9 m^3 of sediment was deposited in the Danjiangkou Reservoir (available at http://www.irtces.org/nishagb_2000.asp). Using a dry bulk density of 1.29 g/cm^3 for the riverine sediment [*Zhu*, 2000], the total dry weight of sediment deposited was 1.81 × 10^9 t. Most of the deposition occurred after 1968 when the reservoir began to impound water (available at http://www.irtces.org/nishagb_2001.asp). The budget of sediment entering the reservoir, deposited in the reservoir and transported out of the reservoir shows that more than 90% of the sediment entering the reservoir was trapped in the reservoir. In spite of the fluctuations of sediment input and deposition, the impounded ratio of sediment (IRS) was stable (Figure 6).

[21] Significant sediment deposition has also occurred in many other reservoirs. In the upper reaches of Yangtze, the examples include the Wujiangdu, Gongzui, Bikou, Gezhouba reservoirs and reservoirs on the Jialingjiang and Jinshajiang rivers (Figure 2; Table 2). *Wang and Peng* [1999] measured sediment deposition in 17 reservoirs along the middle and lower reaches of the river to estimate a cumulative storage capacity of 2.66 × 10^9 m^3 and a cumulative deposition rate of 3.69 × 10^6 m^3/yr (4.76 × 10^6 t/yr assuming a dry bulk density of 1.29 g/cm^3).

[22] Deposition in reservoirs is more rapid in the upper reaches of the river than in the middle and lower reaches. For example, the Three Gorges, Wujiangdu, Gongzui, Bikou, Gezhouba reservoirs and the reservoirs on the Jialingjiang and Jinshajiang rivers have a cumulative storage capacity of 26.5 × 10^9 m^3 and a cumulative deposition rate of 309 × 10^6 t/yr (Table 2). This yields 11.7 kg/yr of sediment deposited per unit storage capacity. The Danjiang-

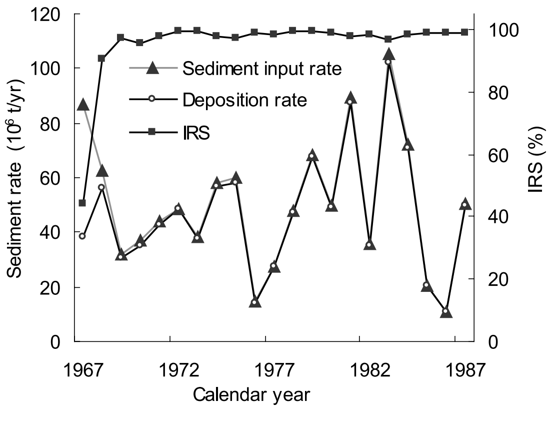

Figure 6. Annual sediment deposition and impounded ratio of sediment (IRS) in the Danjiangkou Reservoir. IRS is the ratio of amount of sediment impounded by the reservoir to the total amount of sediment entering the reservoir (data source is the Yangtze River Water Conservancy Committee).

Table 2. Deposition in Reservoir(s) in the Yangtze River in Comparison to Other Reservoirs

Reservoir(s)	River	Capacity, 10^9 m^3	IRR,[a] %	DR,[b] 10^6 t/yr	IRS,[c] %	RDARR,[d] %	Period
Three Gorges	Yangtze	13.55[e]	3.19	134.4[f]	60.0	100	Jun–Dec 2003
Danjiangkou	Hanjiang[g]	17.45	44.3	71.7	90.8	100	1968–1994
Gezhouba	Yangtze	1.58	0.36	8.3	1.68	100	1981–2000
Gongzui	Daduhe[g]	0.32	0.72	13.3	44.3	100	1967–1987
Wujiangdu	Wujiang[g]	2.15	14.53	72.8			1979–1998
Bikou	Bailongjiang[g]	0.52	6.01	16.6	64.6	100	1975–1996
Reservoirs	Jialinjiang[g]	5.58	7.95	46	32.9	26	1996
Reservoirs	Jinshajiang[g]	2.81	1.85	17.4	7.08	3.1	1996
Panjiakou	Luanhe	2.93	62.1	21.2	95.4	100	1980–1988[h]
Reservoirs	Ebro	7.7	57	144	96	96	1916–2000[i]

[a] Impounded ratio of runoff (the ratio of capacity to annual runoff flowing through the reservoir).

[b] Deposition rate.

[c] Impounded ratio of sediment (the ratio of sediments impounded by reservoir to the sediment entering the reservoir).

[d] Ratio of drainage area regulated by reservoir(s). For single reservoirs, it is 100%. For reservoirs in a river system, it is the ratio of the accumulative area regulated the reservoirs to the total river drainage basin area.

[e] The average of capacities at 135 and 140 m above sea level.

[f] Of the 134.4×10^6 t/yr deposition, 124×10^6 t/yr deposition was observed from June through December, and the rest was simulated according to the IRS from June through December.

[g] Tributary in Yangtze River system.

[h] From *Qian* [1994].

[i] From *Batalla et al.* [2004].

kou reservoir (Table 1) and the 17 reservoirs studied by *Wang and Peng* [1999] in the middle and lower reaches, on the other hand, have a combined storage capacity of 20.1×10^9 m^3 and a combined deposition rate of 76.5×10^6 t/yr, yielding 3.81 kg/yr of sediment deposited per unit storage capacity. This difference can probably be attributed to the spatial variation in suspended sediment concentration (SSC).

[23] During the 1950s, when SSC in the Yangtze River was not significantly influenced by reservoirs, the mean SSC was 1.22 kg/m^3 in the upper reaches of Yangtze (Yichang Station) and 0.278 kg/m^3 in the tributaries of the middle and lower reaches of Yangtze. These values are based on water and sediment discharges at Yichang and Datong stations and the amount of sediment deposited in the middle and lower reaches of Yangtze. The combined storage capacity of reservoirs shown in Table 2 and mentioned by *Wang and Peng* [1999] is 46.6×10^9 m^3, accounting for only 23.3% of the present 200×10^9 m^3 total storage capacity of the Yangtze basin. The combined deposition rate in the reservoirs listed in Table 2 and mentioned by *Wang and Peng* [1999] is 390×10^6 t/yr.

[24] If the total deposition rate in reservoirs throughout the catchment was proportional to the total reservoir storage capacity shown above, the total deposition rate would be 1.67×10^9 t/yr. However, one must account for the fact that riverine sediment is derived mainly from the upper reaches of the river and reservoir sediment deposition rates should not maintain a consistent ratio to reservoir storage capacity as one moves downstream. More than 45×10^3 additional reservoirs accounting for more than 153×10^9 m^3 in storage capacity have been constructed in the tributaries of the middle and lower reaches of Yangtze and remain largely unstudied [*Zhu*, 2000; *CCYRA*, 1993, 1994, 1995, 1997, 1998, 1999, 2000, 2001, 2002, 2003]. If all the additional unstudied reservoirs were located in the tributaries of the middle and lower reaches of the river with a combined deposition rate proportional to that of the similar studied reservoirs in the tributaries in the same areas (the Danjiangkou Reservoir and the 17 reservoirs mentioned by *Wang and Peng* [1999]), then the total deposition rate would be 390×10^6 t/yr + 584×10^6 t/yr = 974×10^6 t/yr. This estimate is significantly lower than the deposition rate estimated by assuming a constant ratio of sediment deposition to reservoir storage capacity throughout the catchment.

[25] This estimate may still be inaccurate because (1) the distribution of unstudied reservoirs in the upper reaches, although fewer in number and lower in capacity than in the middle and lower reaches (Figure 2) [*Zhu*, 2000; *CCYRA*, 1993, 1994, 1995, 1997, 1998, 1999, 2000, 2001, 2002, 2003], is not taken into account and (2) the deposition rates in reservoir complexes may be lower than the sum of the deposition rates in the same reservoirs treated as a series of single reservoirs. For example, in recent years, the deposition rate in Danjiangkou Reservoirs was reduced because new dams were constructed upstream of the Danjiangkou Dam (available at http://www.irtces.org/nishagb_2002.asp).

[26] The sediment trapping efficiency of dams in the Yangtze catchment depends not only on the storage capacity of reservoirs, but also the ratio of storage capacity to runoff. For reservoirs listed in Table 2, the impounded ratio of sediment (IRS) is logarithmically related to the impounded ratio of runoff (IRR), the ratio of water storage to annual discharge (Figure 7). The higher the IRR, the longer the residence time, and the more the suspended particles settle. The relationship of IRR to IRS in Panjiakou Reservoir in the Luanhe River, a river in north China (Table 2), is consistent with the relationship shown in Figure 7. Furthermore, IRR to IRS data from the Ebro river system in northern Spain (Table 2) suggests that this logarithmic relationship may hold true in other river systems when the ratio of drainage area regulated by reservoirs (RDARR) is near 100%.

[27] The total deposition rate in reservoirs in the Yangtze catchment increased with total storage capacity and sediment yield. The area of soil erosion in the river basin increased from 350 km^2 in the early 1950s to 711 km^2 in 2002 (Table 3). The population in the river basin also increased from 178 million to more than 400 million [*Zhang*, 2000]. Soil erosion in the Yangtze catchment can

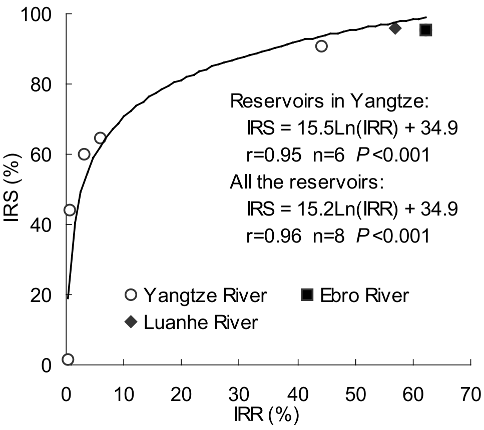

Figure 7. Impounded ratio of runoff (IRR) and IRS (data source is Table 1).

mainly be attributed to deforestation, land use, and mining [*Shi*, 1999; *Zhang and Zhu*, 2001].

[28] Major changes in soil erosion appear due to large but pulsed increases in soil erosion rather than at a constant rate over time. The first major increase of soil erosion occurred during 1958–1959, that is the period of the nationwide “Great Leap Forward” for industrial development that resulted in severe deforestation. A second major increase occurred in the early 1980s when the full modernization in China began. Since then, land use for cultivation, mining and road construction has been greatly intensified. The third major increase occurred in 2001–2002 (Table 3). This increase was probably due to recent economic innovation in west China. Almost all soil erosion increases in 2001–2002 were in the upper reaches of Yangtze River in west China. Overall, a striking increasing trend in soil erosion over last 50 years occurred over the entire basin (Table 3). Sediment yield was positively correlated with the area of soil erosion in the river basin to show that sediment yield in the Yangtze catchment dramatically increased over the past half century (Figure 8).

[29] There are three major depositional sinks for riverine sediment: (1) reservoirs; (2) lakes and channels and related environments; and (3) the coastal ocean. Table 4 shows the sediment budget of the Yangtze River. The total sediment deposition rate in reservoirs increased from almost zero in early 1950s to ~740 × 10^6 t/yr in 2002 (Table 4). This estimate takes into account the effect of soil erosion controls. If soil erosion controls were not included, the total deposition rate in reservoir in 2002 would be significantly higher at about 950 × 10^6 t/yr. Assuming that soil erosion and sediment yield data in 2003 are consistent with 2002 data taking soil erosion control into account, total deposition in reservoirs would amount to nearly 860 × 10^6 t/yr, given that TGD trapped 124 × 10^6 t of sediment in 2003 (available at http://www.irtces.org/nishagb_2003.asp).

Table 3. Areas of Soil Erosion and Soil Erosion Control in the Yangtze River Catchment From the 1950s to 2002[a]

	Soil Erosion		Soil Erosion Control		
Calendar Year	Upper Reaches	Whole Basin	Upper Reaches	Whole Basin	References
1951		350			*Shi* [2002]
1985	352	562			*Zhu* [2000], *Shi* [1999]
1992	346	572	54	157	*CCYRA* [1993]
1993	347	573	52	160	*CCYRA* [1994]
1994	347	572	66	177	*CCYRA* [1995]
1996	380	613	81	199	*CCYRA* [1997]
1997	368	600	74	197	*CCYRA* [1998]
1998	368	600	58	186	*CCYRA* [1999]
1999	370	603	90	240	*CCYRA* [2000]
2000	370	603	97	243	*CCYRA* [2001]
2001	460	707	103	243	*CCYRA* [2002]
2002	472	711	110	251	*CCYRA* [2003]

[a] Areas are in 10^3 km^2.

[30] As opposed to the increasing trend in sediment deposition rate in reservoirs, Figure 9 and Table 4 show that there has been a decreasing trend in deposition in the lakes [*Wu et al.*, 2002]. Table 4 also indicates that sediment trapped by dams begins to exceed the amount of sediment supply to the East China Sea in early 1980s. Analysis of 3 year running averages indicates that overall there has been a decreasing trend in the seaward sediment supply from the Yangtze River (Figure 10). The annual deposition in reservoirs in the catchment in 2003 was 4.2 times that of the sediment supply to the sea (206 × 10^6 t).

[31] Similar trends in sediment deposition rates in reservoirs were found in other river systems. For example, in the United States, the total storage capacity and deposition rate of reservoirs is 500 × 10^9 m^3 and 1.2 × 10^9 m^3/yr, respectively [*Han*, 2003]. In India, the total storage capacity and deposition rate of reservoirs reached 126 × 10^9 m^3 and 0.63–1.26 × 10^9 m^3/yr [*Han*, 2003]. In the catchments of the Nile [*Stanley and Warne*, 1998; *Frihy et al.*, 2003], the Ebro [*Sánchez-Arcilla et al.*, 1998] and Luanhe [*Qian*, 1994], almost all the riverine sediment are now deposited in reservoir.

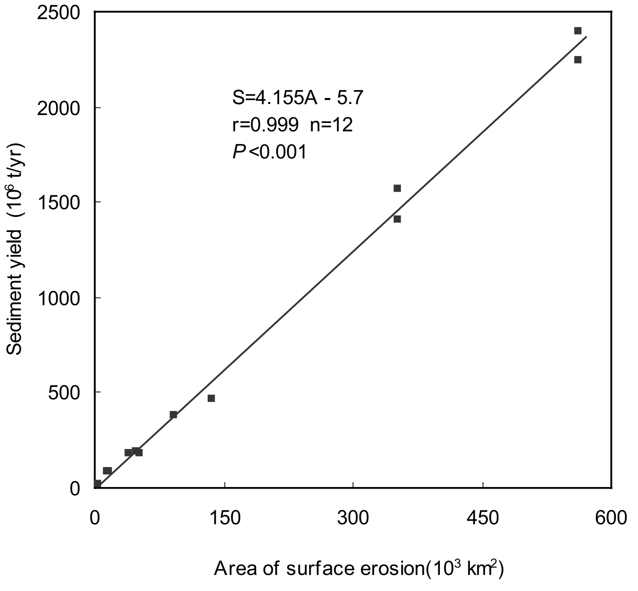

Figure 8. Regressive relationship between area of soil erosion (*A*) and sediment yield (*S*) in the Yangtze catchment (data sources are *Shi* [1998, 2002], *Zhang et al.* [1999], *Zhang and Zhu* [2001], and *Jiang and Huang* [2003]).

Table 4. Sediment Budget of the Yangtze River Basin

Period	Soil Erosion, 10^3 km^2	Soil Erosion Control, 10^3 km^2	Sediment Yield, 10^6 t/yr	Sediment Entering the River, 10^6 t/yr	Net Deposition in Lakes and Channels, 10^6 t/yr	Supply to the Sea,[a] 10^6 t/yr	Deposition in Reservoirs, 10^6 t/yr
1951	350		1449[b]	599	195[c]	403	<1[d]
1985	562		2320[e]	951[f]	108[c]	403	440[g]
2002	711	251	2427[b,h]	995[e]	−17[i]	275	737[g]

[a] Datong Station.

[b] Based on the regressive relationship between sediment yield and area of soil erosion in Figure 8.

[c] Most of the net deposition occurred in Lake Dongting based on http://www.irtces.org/nishagb_2000.asp, http://www.irtces.org/nishagb_2001.asp, and *Wu et al.* [2002].

[d] Based on Figure 5 and the ratio of deposition in reservoirs of the upper reaches to the whole river basin.

[e] Based on *Shi* [1998] and *Zhang and Zhu* [2001].

[f] According to the sediment budget in 1951, the transport ratio was (195 + 403 + 1)/1449 = 0.41, where 195, 403, 1, and 1449 (10^6t/yr) were net deposition in lakes and channels, sediment supply to the sea, deposition in reservoirs, and sediment yield, respectively. This ratio is near the estimate of 0.3–0.5 by *Shi* [1999]. The amount of sediment entering into the river system was calculated by multiplying the sediment transport ratio with the sediment yield.

[g] Sediment entering into the river system subtracted by deposition in lakes and channels and sediment supply to the sea.

[h] The soil erosion control was taken into account. In the soil erosion control areas the sediment yield rate was about half as large as the soil erosion areas [*Zhang*, 2004]. Thus in the calculation of sediment yield using $S = 4.155A - 5.7$ (Figure 8), $A = A_{se} - 1/2A_{sec}$, where A_{se} is area of surface erosion and A_{sec} is the area of soil erosion control.

[i] In 2002, sediment discharges were 228 × 10^6 t at Yichang and 275 × 10^6 t at Datong, and the total sediment discharge from the tributaries between Yichang and Datong were ≈30 × 10^6 t (http://www.irtces.org/nishagb_2002.asp), which suggests a −17 × 10^6 t net deposition in the lakes and channels between Yichang and Datong.

4.3. Reduction in Sediment Supply to the Sea

[32] Although annual sediment load in the Yangtze River varied over time, there has been a strong decreasing trend in seaward supply since the mid 1960s (Figure 10). Fluctuations in annual sediment discharge may be attributed to the changes in annual precipitation and water discharge [*Yang et al.*, 2003]. Observed annual sediment discharge decreased from a maximum of 679 × 10^6 t/yr in 1964 to a minimum of 206 × 10^6 t/yr in 2003 (available at http://www.irtces.org/nishagb_2000.asp, http://www.irtces.org/nishagb_2001.asp, http://www.irtces.org/nishagb_2002.asp, http://www.irtces.org/nishagb_2003.asp), and the 3 year running average sediment discharge decreased from a maximum of 563 × 10^6 t/yr in 1965 to a minimum of 252 × 10^6 t/yr in 2002 (Figure 10). A linear regression fit to the 3 year running average sediment discharge versus time shows a decrease in sediment discharge of about 50% from 1965 to 2002 (Figure 10). Major variations in sediment discharge were in phase with the fluctuations of water discharge (Figure 11) may be attributed to local climate changes (e.g., weather and precipitation patterns).

[33] The decreasing trend in annual sediment discharge to the sea discussed above can be attributed to increased sediment storage in the reservoirs because, during the same period: (1) annual precipitation [*Wang et al.*, 2002] and water discharge (Figure 11) have not shown an overall decreasing trend; (2) annual sediment yield has increased in parallel with soil erosion (Table 3) [*Higgitt and Lu*, 2001; *Lu and Higgitt*, 2001; *Yin and Li*, 2001]; and (3) deposition in lakes and channels in the river system has decreased (Figure 9; Table 4). Further evidence to support this assertion can be found in records of sediment discharge and water discharge. For example, from 1967 to 1969, sediment discharge decreased sharply even though water discharge was dramatically increased (Figure 11). This is related to water impoundment at the Danjiangkou reservoir, the largest reservoir before construction of TGD. From 2002

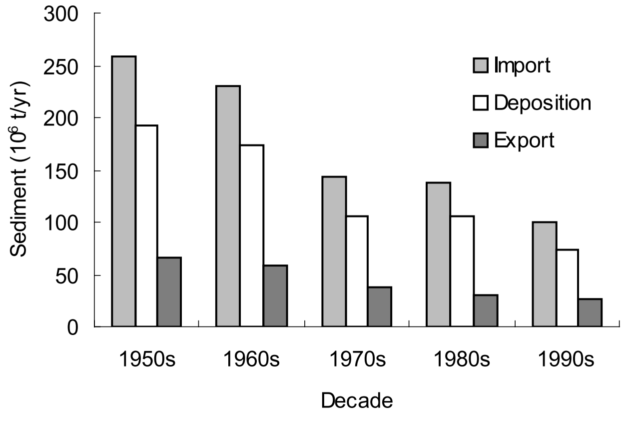

Figure 9. Sediment budget for Lake Dongting from the 1950s to the 1990s (data sources are *Wu et al.* [2002] and *Li and Wang* [2002]).

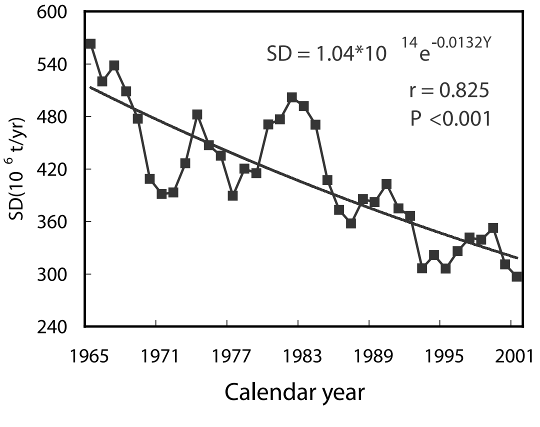

Figure 10. Three year running average sediment discharge (SD) at Datong Station from 1965 to 2001 (*Y*, number of years) (data source is the Yangtze River Water Conservancy Committee).

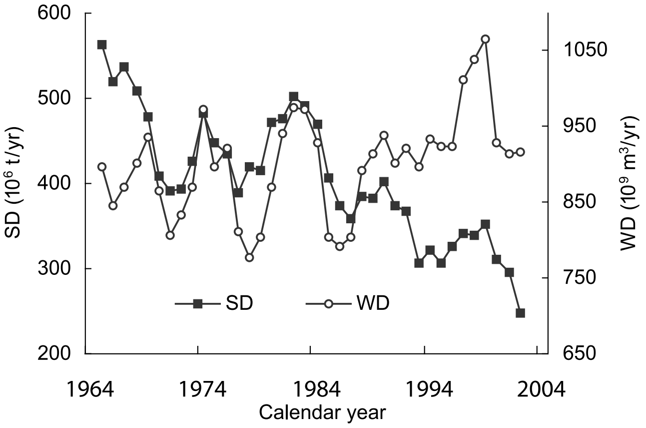

Figure 11. Three year running average SD and water discharge (WD) at Datong Station from 1965 to 2003 (data source is the Yangtze River Water Conservancy Committee).

to 2003, sediment discharge decreased by 25% while water discharge decreased by only 7%. The decrease in sediment discharge was mainly due to the deposition in TGD Reservoir from June to December 2003. The overall decrease in sediment discharge caused by TGD is shown by the comparison of 3 year running average water discharge and sediment discharge from 2001 to 2002 in Figure 11.

[34] Dams have also reduced the grain size of sediment delivered to the sea. The median size at Datong was 0.027 mm during 1956–1976 (based on data from the Yangtze River Water Conservancy Committee), 0.017 mm during 1976–2000 (available at http://www.irtces.org/nishagb_2000.asp), and 0.010 mm during 2001–2003 (based on data from http://www.irtces.org/nishagb_2001.asp, http://www.irtces.org/nishagb_2002.asp, http://www.irtces.org/nishagb_2003.asp). The decrease in grain size is because reservoirs selectively trap a larger proportion of coarse-grained sediments relatively to fines.

4.4. Response of Delta Intertidal Wetlands

[35] The progradation rate of intertidal wetlands in eastern Chongming and eastern Hengsha decreased from 11.1 km^2/yr in 1971 to 1.9 km^2/yr in 1991. Progradation changed to recession from 1991 to 1998. In contrast, the recession of intertidal wetland in eastern Nanhui weakened from 1971 to 1983 and changed to progradation from 1983 to 1998. The progradation rate of intertidal wetland in Jiuduansha increased from 1.9 km^2/yr in 1971 to 3.3 km^2/yr in 1998 (Table 1). The trends of the four intertidal wetlands as a whole suggest an overall southward shift in the major depocenter (Table 1), probably due to a southward shift in riverine water flow and sediment supply to the sea (see Figure 1). This southward shift is part of the natural evolution of the Yangtze mouth over the past 2000 years [*Chen et al.*, 1988a, 1988b]. According to *Yun* [2004], from 1971 to 1998, the flow volume of the North Branch decreased by 33% while the flow volume of the South Branch system increased by 35%. The enlargement of the South Branch system is expected to permit more riverine water and sediment to pass.

[36] In spite of the differences in growth rate trends among the individual wetlands, the total growth rate of these four intertidal wetlands shows an overall decreasing trend (Table 1). Using regression techniques (SPSS 12.0 software), total growth rate was found to be significantly correlated with riverine sediment discharge. The total growth rates during seven periods derived from Table 1, and the riverine sediment discharges during the corresponding periods were based on the annual sediment discharges shown in Figure 10. The relationship between total growth rate and riverine sediment discharge is

$$Gr = 0.0559Sd - 14.7, \tag{1}$$

where Gr represents total growth rate (km^2/yr) of the studied intertidal wetlands and Sd represents sediment discharge (10^6 t/yr) at Datong Station. The correlation coefficient, r, for the above relation is 0.88, and the with data number $n = 7$ and significance level $P < 0.01$. When $Gr = 0$, equation (1) shows $Sd = 263$. Therefore when Sd is $<263 \times 10^6$ t/yr at Datong, recession will occur on the studied intertidal wetlands. In 2003, due to TGD, Sd was 206×10^6 t/yr at the Datong Station (available at http://www.irtces.org/nishagb_2003.asp) below this threshold value. This suggests that intertidal wetlands as a whole may begin to degrade if the natural conditions at the intertidal wetlands are not interfered by engineering projects.

[37] The loss of intertidal wetlands can be caused by sediment erosion, and sediment compaction and subsidence under the load. When the riverine sediment supply is insufficient to balance the combined rate at which the marine currents are transporting sediment away from the delta and the rate at which the delta is sinking, wetlands will be lost rather than gained. In this regard, the riverine sediment supply is the governing factor the evolvement of the deltaic wetlands.

[38] Figure 12 shows a conceptual model for the intertidal wetland response to decrease in riverine sediment supply. In Figure 12, the following are assumed: (1) the wetland is initially growing; (2) the deposition rate decreases with riverine sediment supply; (3) the deposition rate can be +

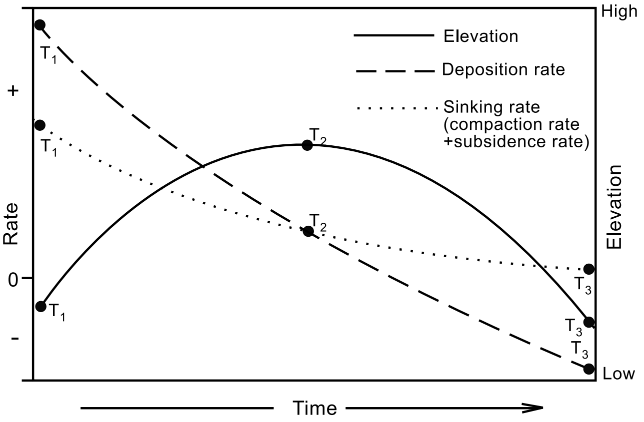

Figure 12. A conceptual model of intertidal wetland response to changes in deposition and sinking rates.

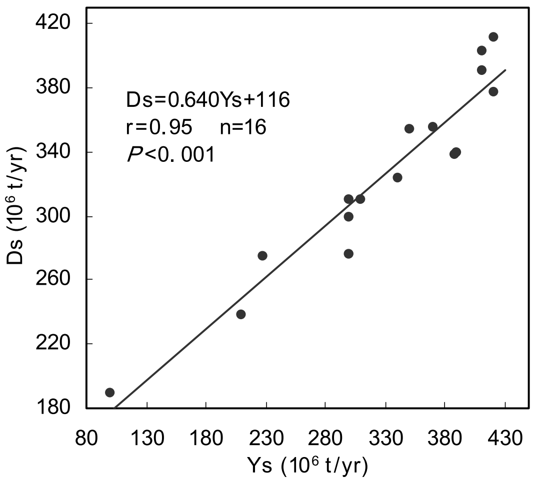

Figure 13. Regressive relationship between sediment discharges less than 420 t/yr at Yichang (Ys) and Datong (Ds) hydrographic gauging stations (data source is the Yangtze River Water Conservancy Committee).

or − (sediment erosion); and (4) although the sinking rate (compaction rate + subsidence rate) decreases with deposition rate, it decreases more slowly than deposition rate. From T_1 to T_2, deposition rate is higher than sinking rate, which leads to increase in intertidal wetland elevation. However, the growth of the intertidal wetland slows down with decrease in difference between deposition rate and sinking rate. At T_2, deposition rate equals sinking rate and the intertidal wetland stops growing. From T_2 to T_3, deposition rate is insufficient to counteract sinking rate, which leads to decrease in elevation of the intertidal wetland. At this stage, the loss of wetland is accelerating because the difference between sinking and deposition rates is getting greater. As a result, the temporal trend of the intertidal wetland surface elevation with a steadily decreasing sediment deposition rate is arched.

[39] The overall relationship between growth rate and riverine sediment supply was unclear when the intertidal wetlands were studied individually. The growth rates of the intertidal wetlands at Jiuduansha and eastern Nanhui showed increasing trends from 1971 to 1998 (Table 1). This suggests a negative relationship between growth rate (Table 1) and sediment supply (Figure 10). This relationship, however, does not account for the allotment of riverine sediment among the river mouth outlets and the interaction with the coastal hydrodynamics. It has been shown that almost all the riverine sediment supply to the coastal ocean from the Yangtze River was transported via the three outlets of the North Channel, North Passage, and South Passage between the eastern Chongming, eastern Hengsha, Jiuduansha and eastern Nanhui (Figure 1) [*Yang et al.*, 2001b, 2003]. Therefore the total growth rate of these four intertidal wetlands in combination, rather than individually, should account for the distribution of riverine sediment between the three outlets. Overall the decreasing trend in total growth rate (Table 1) corresponds well to the decreasing trend in riverine sediment supply (Figure 10).

[40] It should be noted that the relationship between intertidal wetland growth rate and riverine sediment supply discussed above does not include the decrease in grain size mentioned earlier and the relative allotment of fine-grained sediments between the intertidal area, subtidal area, and the coastal ocean. The finer sediment is expected to be more likely to bypass the delta, making it out to deeper waters without trapping on the delta to aid in formation of wetlands. A great quantity of sediment supplied by the Yangtze River is transported off the delta by littoral currents [*Yang et al.*, 2000]. The influence of coastal sediment transport process on the growth rates of the intertidal wetland discussed in this study sheds light on the significance and directs toward an area for future research.

4.5. Significance of Changes in Riverine Sediment Supply to the Management of Delta Intertidal Wetlands

[41] Since TGD was put into operation in June 2003, strong sediment deposition in the reservoir has occurred. The IRR of the TGD reservoir (Table 1) is predicted to be 8.8% at the 175 m water level in 2009. According to the regression equation for the Yangtze Rivers reservoirs shown in Figure 7, IRS at TGD will be 69% when the water level rises to 175 m above sea level. In other words, nearly 70% of the sediment from the upper reaches of the Yangtze River will be trapped by the TGD reservoir. Furthermore, according to *Yangtze River Water Conservancy Committee* [1999] (available at http://www.irtces.org), due to the trapping effects of other dams recently constructed up river from TGD, sediment entering TGD has been reduced to from 299 × 10^6 t/yr in 2001 to 224 × 10^6 t/yr in 2003. Several additional dams, with accumulative reservoir storage capacities greater than TGD, are currently being constructed or are planned for construction in the upper reaches of the river [*Zhu*, 2000]. These dams will further reduce the amount of sediment entering the TGD reservoir. In the coming decades, due to construction of new dams [*Zhu*, 2000] and afforestation [*Yang et al.*, 2003] upstream of TGD, sediment entering TGD will likely reach <200 × 10^6 t/yr (estimate of this study). Because 70% of the sediment entering the TGD reservoir will be trapped by TGD [*Yang et al.*, 2002], sediment flowing out of TGD will likely be <60 × 10^6 t/yr.

[42] Figure 13 reflects the regulative effect of the middle and lower reaches of the river on sediment transport. According to the equation shown in Figure 13, sediment discharge at Datong is less than the sediment discharge at Yichange when sediment discharge at Yichange is >322 × 10^6 t/yr. In this case, deposition in lakes and channels of the middle and lower reaches of the river is greater than sediment supply from the tributaries in these reaches. However, when sediment discharge at Yichang is <322 × 10^6 t/yr, sediment discharge at Datong is greater than sediment discharge at Yichang which suggests that deposition in lakes and channels is less than sediment supply from tributaries. Another possibility is that net erosion occurs in the middle and lower reaches when the sediment discharge at Yichang is low. In 2002 and 2003, net erosion was observed in the middle and lower reaches of the Yangtze River (Table 5). In 2002, sediment discharge was 228 × 10^6 t at Yichang and 275 × 10^6 t at Datong, and the total sediment supply from the tributaries between Yichang and Datong was ~30 × 10^6 t, which suggests a net erosion of 17 × 10^6 t of sediment between Yichang and Datong. In

Table 5. Sediment Budget Between Yichang and Datong[a]

Year	Sediment Discharge at Yichang[b]	Total Sediment Discharge of the Tributaries[b]	Sediment Discharge at Datong[b]	Net Erosion Between Yichang and Datong
2002	228	30	275	17
2003	98	40	206	68

[a]Sediment budgets are in 10^6 t.
[b]Data from http://www.irtces.org/nishagb_2002.asp and http://www.irtces.org/nishagb_2003.asp.

2003, sediment discharge was 98 × 10^6 t at Yichang and 206 × 10^6 t at Datong. The total sediment supply from the tributaries between Yichang and Datong was ∼40 × 10^6 t, suggesting a net erosion of 68 × 10^6 t of sediment between Yichang and Datong (Table 5).

[43] The regression equation in Figure 13 suggests that the sediment discharge at Datong will be <154 × 10^6 t/yr, given a <60 × 10^6 t/yr sediment discharge at Yichang (as shown above). Therefore Yangtze sediment discharge in the coming decades can be expected to be much less than the threshold value below which the delta intertidal wetlands degrade. The effects of delta degradation will be reflected differently by each of the individual wetlands in this region but overall, in the absence of management action for the purpose of recession prevention and accretion promotion, a net loss of total intertidal wetland area in the Yangtze River delta can be expected.

5. Summary and Conclusions

[44] Around 50,000 dams were constructed in the Yangtze River catchment from the 1950 to 2003. The total storage capacity of the reservoirs is now nearly 200 × 10^9 m^3, or 22% of the annual water discharge. With the increased number of dams in the catchment, more and more sediment is being trapped in reservoirs. In the late 1960s, riverine sediment supply to the sea began a decreasing trend, even though sediment yield has increased along with soil erosion. In the early 1980s, sediment deposited in reservoirs began to exceed the sediment supply to the sea. At present, around 850 × 10^6 t/yr of sediment is deposited in reservoirs. Without dam construction, the Yangtze River sediment supply to the sea would have amounted to about 800 × 10^6 t/yr, even if deposition in lakes and river channels was taken into account. Owing to the impacts of TGD and other new dams, however, Yangtze River sediment discharge in the coming decades will probably be reduced to <150 × 10^6 t/yr. Intertidal wetlands at the delta front, as a whole, were shown to be sensitive to changes in riverine sediment supply, although different responses exist among individual wetlands. The total growth rate of intertidal wetlands in the Yangtze delta front decreased from ≈12 km^2/yr in the early 1970s to 3.3 km^2/y in 1998. Predicted sediment discharge in the coming decades will be much less than the estimated threshold value below which overall intertidal wetland degradation will occur. Thus intertidal wetlands in the Yangtze River delta as a whole (which include eastern Chongming and Jiuduansha Shoal, both national wetland reserves) will degrade unless action in basin-wide water management strategies or effective countermeasures are adopted to prevent degradation. This will have a significant impact on environments of the delta and nearby coastal ocean.

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