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Climatic and Anthropogenic Impacts on Water and Sediment Discharges from the Yangtze River (Changjiang), 1950–2005

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29.1 INTRODUCTION

Rivers form the major links between land and ocean through their transfer of water and sediment. Fluvial discharges to the oceans, however, are unevenly distributed in both space and time, in large part influenced by both climatic (e.g. precipitation) and anthropogenic (e.g. dam construction) forcings.

The global water system has been greatly impacted by humans (Vorosmarty *et al*., 2003), and more than half the world's large river systems are significantly affected by dams or water diversions (Syvitski *et al*., 2005; Nilsson *et al*., 2005). Considering projected climate change and growing demographic pressures, the availability and quality of freshwater have become increasing concerns (Gleick, 1993, 2000; Shiklomanov and Rodda, 2003). Nowhere are these concerns more acute than in southern Asia, where water withdrawal has increased about fourfold since 1950 (Shiklomanov, 1999). China and India alone account for more than 40 % of the global freshwater used for irrigation (Gleick, 2000), and since 1950, China has built almost half the world's large dams higher than 15 m (Fuggle and Smith, 2000).

Historically, terrestrial erosion has accelerated in response to deforestation and land cultivation, but in recent years sediment delivery from many rivers has decreased following construction of large dams. Those on the Colorado and Nile Rivers, together with extensive downstream irrigation systems, have resulted in almost total elimination of riverine sediment discharges to the coastal regions. As a result, the deltas of these two rivers are actively receding (Stanley and Warne, 1998; Carriquiry *et al*., 2001). In the Yellow River, the impact from dam construction has been greatly amplified by decreased precipitation, leading to increased water consumption (Wang *et al*., 2006); water and sediment discharges now are <15 % of the 1950–1960s levels, and its once-prograding delta is now being eroded (Chu *et al*., 2006).

The basin of the Yangtze River (Changjiang, Figure 29.1) is home to 400 million inhabitants and includes >50 000 dams within its boundaries, making it one of the most highly impacted rivers in the world (Nilsson *et al*., 2005; Yang, Z.S. *et al*., 2006). Recent climatic change in the Yangtze drainage basin has resulted in more melting of snow and ice at higher elevations (Wu, 2000; Chen, X. *et al*., 2001; Cyranoski, 2005), significant decline in regional annual precipitation over the northern tributaries, as well as more frequent and extreme flooding in recent years (Menon *et al*., 2002; Xu *et al*., 2005).
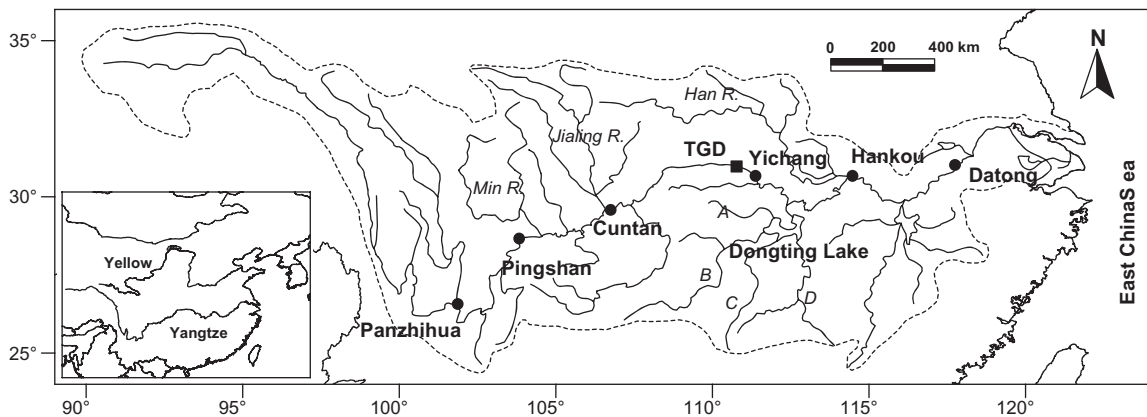
Figure 29.1   Yangtze River drainage basin. Dots represent six major gauging stations along the main stream. TGD, Three Gorges Dam. Four southern tributaries (A, Lishui River; B, Yuan River; C, Zishui River; D, Xiang River) flow into Dongting Lake and then enter the mainstem. Traditionally the Yangtze is divided into upper (above Yichang), middle (Yichang to Hankou) and lower (downstream of Hankou) reaches

Numerous anthropogenic activities also have increasingly impacted the Yangtze since the 1950s. Water withdrawal and consumption of the Yangtze have expanded about fourfold as the population has doubled and irrigation withdrawals have increased (Ren *et al*., 2002). Since 1988, sediment discharges in headwater streams have decreased greatly due to the Yangtze Water and Soil Conservation Project. Moreover, since June 2003, the Three Gorges Dam (TGD, the world's largest in terms of hydropower-generating capacity) also started to impound both water and sediment. With full operation of TGD to begin in 2009, its threatening impact to the channel downstream of the dam and the coastal ecosystems is a cause for acute concern (Xie *et al*., 2003; Shen and Xie, 2004). Plans for future large dams upstream of the TGD and the proposed south–north water diversions, almost certainly will accentuate existing anthropogenic impacts on the Yangtze.

In the past two decades, more than 100 papers have been published on water and sediment variations of the Yangtze River (Shi *et al*., 1985; Liu and Zhang, 1991; Zhang, 1995; Higgitt and Lu, 1996; Deng and Huang, 1997; Chen, Z. *et al*., 2001; Yang *et al*., 2002; Zhang and Wen, 2004; Yang, Z.S. *et al*., 2006), but few have been able to (a) address both spatial and temporal change of the whole Yangtze in a comprehensive way, (b) delineate and compare sub-basin variations, and (c) quantitatively separate climatic impacts from the human ones. In this chapter we discuss the spatial and temporal trends of both water and sediment fluxes of the Yangtze drainage basin from 1950 to 2005, and attempt

to quantify the river's responses to various impacts. Specifically, we ask how have basin-wide and sub-basin water and sediment discharges responded to climatic (e.g. precipitation) as opposed to anthropogenic (e.g. dams) forcings? Given the recent changes within the basin, what can we expect in the future and how will the coastal regions respond to these changes?

29.2 PHYSICAL SETTING

Draining a basin of $1.8 \times 10^6 \, \text{km}^2$, the largest in southeastern Asia, the Yangtze River is one of the world's biggest rivers in terms of both water (5th; $900 \, \text{km}^3 \text{year}^{-1}$) and sediment discharges (4th; 480 million tons year^{-1}) (Milliman and Meade, 1983; Milliman and Syvitski, 1992; Meade, 1996). Originating in the Qinghai-Tibet Plateau (Saito *et al*., 2001), the Yangtze drains high mountains and flows through steep valleys in its upper reaches, meanders across low-gradient alluvial plains in its middle and lower courses, and merges with numerous northern and southern tributaries before debouching into the East China Sea (Figure 29.1). Mean annual precipitation rapidly increases in the downstream direction, from <400 mm in the northwest to >1600 mm in the southeast; with the basin-wide annual precipitation averaging 1050 mm (Figure 29.2). Rainfall in the Yangtze Basin follows a typical monsoonal regime (Shi *et al*., 1985), with more than 60 % of annual precipitation falling during the wet season (March–August in the middle and lower sections; May–September farther upstream).
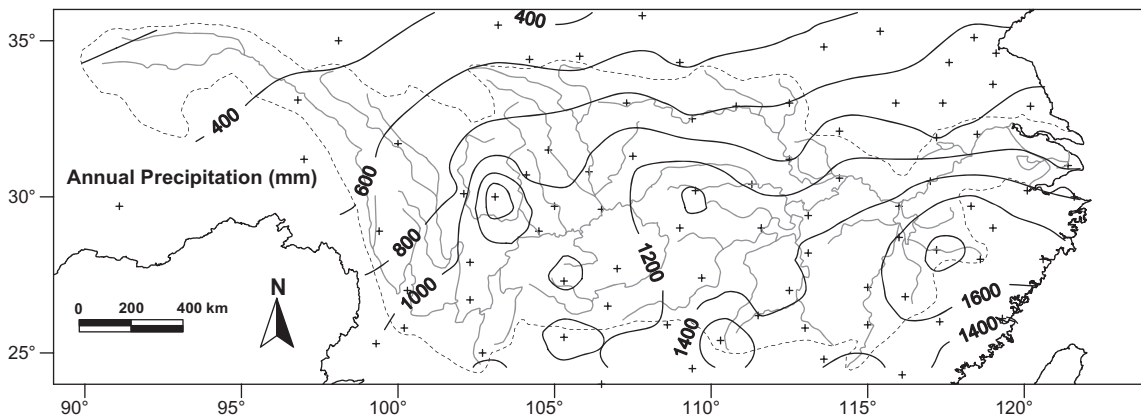
Figure 29.2   Mean annual precipitation (mm) in Yangtze drainage basin, 1951–2000. Crosses represent locations of meteorological stations

29.3 DATA AND METHODS

Monthly precipitation data (1951–2000) from 47 meteorological stations throughout the Yangtze Basin (shown as crosses in Figure 29.2) were extracted from a 160-station precipitation dataset released by the Ministry of Meteorology in China. Since these stations are not evenly distributed in space, basin-wide and sub-basin annual average precipitation were determined by interpolation and gridding in a Golden Surfer program after equal-area projection in ArcView GIS software.

Water and suspended-sediment discharges were obtained primarily from the Bulletin of Yangtze Sediment in 2000–2005, Changjiang Water Resources Commission, as well as from published papers (Shi *et al*., 1985; Higgitt and Lu, 1996; Deng and Huang, 1997; Pan, 1997; Lu and Higgitt, 1998; Chen, Z. *et al*., 2001; Shen, 2001; Yang *et al*., 2002; Zhang and Wen, 2004). Since bed load represents only 5% of total sediment discharge from the Yangtze River (Chen, Z. *et al*., 2001), it is not discussed here. Annual water and suspended-sediment discharges from 23 gauging stations were collected to delineate temporal and spatial trends between 1950 and 2005. Runoff was calculated by dividing water discharge by its corresponding drainage basin area upstream from the gauging station. Monthly data were collected from three mainstem stations (Yichang, Hankou and Datong, Figure 29.1). Sediment-yield data were compiled from Liu and Zhang (1991) and Dai and Tan (1996).

Trends for precipitation, runoff, sediment discharges as well as correlation coefficients (R^2) between precipitation and runoff were calculated by linear regression. Nonparametric Mann–Kendall analysis (Mann, 1945; Kendall, 1975) was used to analyze the trends for precipitation and runoff over the same period, its calculation procedure explained in Smith (2000).

29.4 SPATIAL VARIATIONS OF WATER AND SEDIMENT

The Yangtze drainage basin can be divided into four distinct sub-basins (Upper1, Upper2, North and South, Figure 29.3) based on patterns of runoff, sediment yield and sediment concentration. The drainage area upstream from the seaward-most Datong Station incorporates 94% of the entire basin area and represents the basin-wide values (the grey regions in Figure 29.3). A disproportionate amount of Yangtze water comes from the south-east whereas its sediment mostly comes from the upper and northern parts of the basin. Controlled by precipitation (Figure 29.2), the runoff is the lowest in the headwaters (sub-basin Upper1, 300 mm year^{-1}, Figure 29.3) and the highest in the south-eastern tributaries (sub-basin South, 800 mm year^{-1}). In contrast, sediment concentrations are greatest in the upper and northern basins (1.8 kg m^{-3} in sub-basin Upper1) where valleys are steep and soils are erodible, falling to about 0.2 kg m^{-3} toward the south-east (sub-basin South), where the regional tributaries of the Yangtze flow through low-relief alluvial plains.

This spatial pattern leads to matching water and sediment variations (Figure 29.4) noted at six gauging stations (see locations in Figure 29.1) along the Yangtze mainstem. The Yangtze water discharge gradually increases downstream following cumulative contribution from numerous tributaries, reaching a maximum at the seaward-most station at Datong (Figure 29.4). Sediment discharge, in
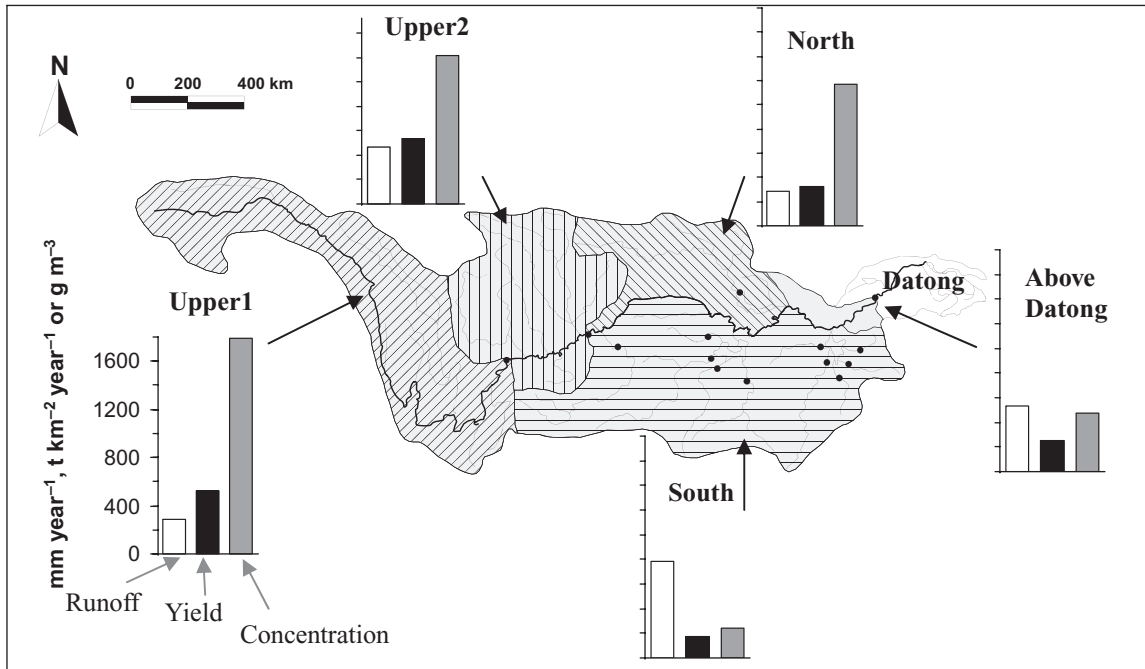
Figure 29.3 Runoff, sediment yield, and suspended-sediment concentrations in the Yangtze sub-basins. Black dots are hydrological stations used for the calculations of sub-basins: Pingshan for sub-basin Upper1, the difference between Cuntan and Pingshan for Upper2, Huangzhuang for the North, and 10 stations (Wulong, Xiangtan, Taojiang, Taoyuan, Shimen, Waizhou, Lijiadu, Meigang, Hushan, Wanjiabu, from west to east) for the South. Datong Station represents 94% the total Yangtze drainage basin. See Figure 29.1 for the locations of the mainstem stations
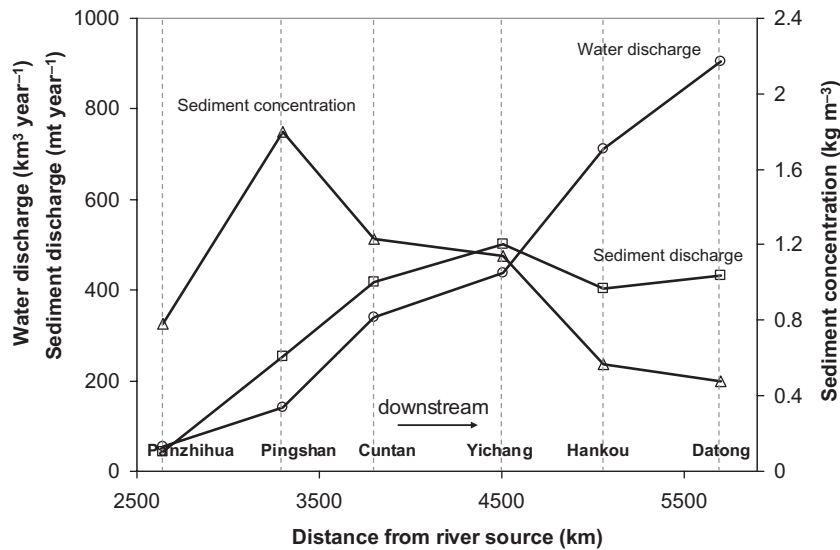

Figure 29.4 Spatial variation of water discharge, sediment discharge, and concentrations along the mainstem of the Yangtze River. These values are generally 1950–2000 means from the Bulletin of Yangtze Sediments (2000–2005). See Figure 29.1 for the locations of the six gauging stations

contrast, shows a maximum at upper reaches at Yichang, decreasing slightly in the middle (Hankou) and lower (Datong) reaches because the river loses sediment into the floodplain channels and lakes (Figure 29.4). Because water discharge increases downstream while sediment discharge decreases, average sediment concentration decreases from $1.8 \, \text{kg m}^{-3}$ in the upper reaches to about 0.5 at Datong.

The combination of steadily increasing water discharge and somewhat decreasing sediment discharge in the lower Yangtze is also typical of the lower reaches of other large alluvial rivers: Ob River of Siberia (Bobrovitskaya *et al*., 1996; Meade *et al*., 2000) and Amazon River of Brazil (see Figure 4.6). Those downstream decreases in suspended sediment (both discharge and concentration) usually are attributable to deposition in the lakes and lowlands on the large floodplains of these rivers.

29.5 TEMPORAL VARIATIONS OF WATER AND SEDIMENT

Superimposed on these spatial variations, various temporal changes have occurred in the Yangtze drainage basin since 1950. Variations in both water and sediment discharges are discussed below at two timescales: annual and monthly.

29.5.1 Annual variations

Water (precipitation and runoff)

During the five decades from 1951 to 2000, annual precipitation increased in the south-east (>100 mm, solid lines in Figure 29.5) while it decreased in the upper reaches (−200 mm, dashed lines in Figure 29.5), particularly in the Jialing and Min tributary basins (Figure 29.1). Sub-basins Upper1 and South showed slightly increased precipitation, whereas a striking decrease in precipitation occurred in Upper2 (−11.0%) and a slight decline in North (Figure 29.6). Correspondingly, runoff (water discharge per unit area) also increased in the Upper1 and South but decreased in the Upper2 and North (Figure 29.6).

Because of limited runoff and precipitation data, precipitation was compared with runoff for the period 1951–2000 for sub-basins North and Above-Datong, but for 1956–2000 for sub-basins Upper1, Upper2 and South (Table 29.1). The statistically significant decrease of runoff (−25.7%, −100 mm) in 1951–2000 in sub-basin North far exceeded the nonsignificant decrease (−2.5%, <24 mm) in precipitation (Table 29.1). By contrast, the increase in runoff (18.6%, 134 mm) over 1956–2000 in sub-basin South was larger than that of precipitation (7.8%, 106 mm) although both trends were significant and the correlation was 0.82 (Figure 29.6; Table 29.1).

Despite these sub-basin changes, water discharges along the mainstem in upper (Pingshan and Yichang stations), middle (Hankou) and lower (Datong) reaches of the Yangtze (Figure 29.1) have varied little since 1950 (Figure 29.7a), reflecting increases in some sub-basins being offset by decreases in others. Basin-wide runoff measured at Datong correlated well with precipitation ($R^2 = 0.83$), but neither showed a significant change over time (Figure 29.6; Table 29.1).
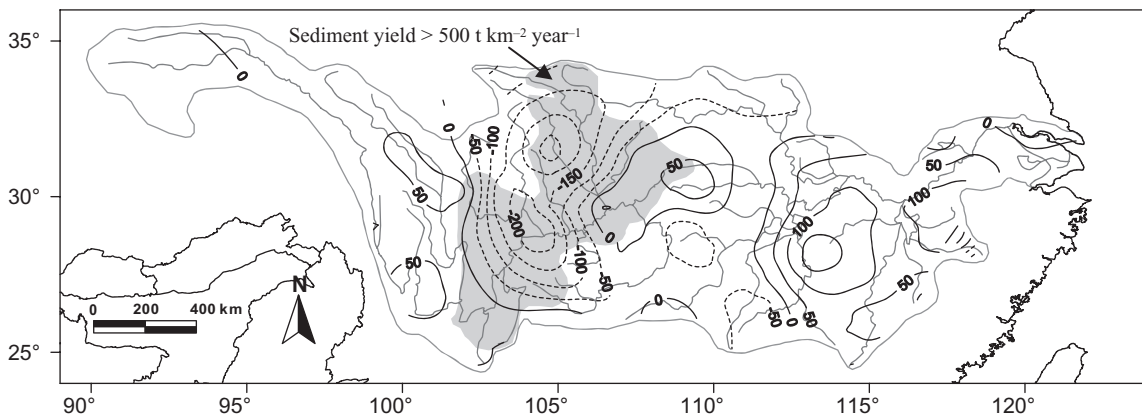

Figure 29.5 Precipitation change (mm) of the Yangtze drainage basin, 1951 to 2000. Solid and dashed lines correspond to increased or decreased precipitation, respectively. The grey area is the region with sediment yields greater than $500 \, \text{t km}^{-2} \, \text{year}^{-1}$ (modified after Liu and Zhang, 1991; Dai and Tang, 1996)
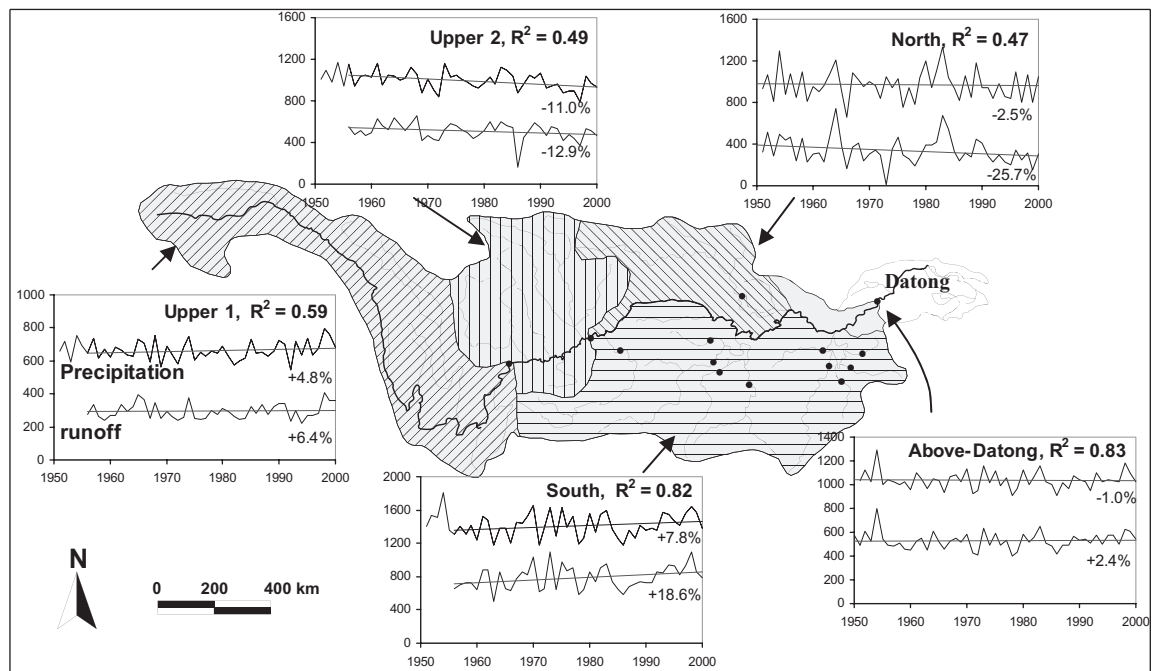
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Figure 29.6 Spatial and temporal variations of precipitation and runoff in the Yangtze, 1950–2000. Upper and lower lines are average annual precipitation and runoff (in mm) for sub-basins along with their trends in percentages. Correlation coefficient (R^2) between precipitation and runoff is marked in each panel. Black dots are gauging stations used for the calculations of cumulative runoff. Datong Station covers 94% the total Yangtze drainage basin. See Figure 29.3 for station explanation and Table 29.1 for the results of Mann–Kendall analyses

Table 29.1 Mann–Kendall trend analyses of precipitation and runoff from the sub-basins of the Yangtze River

Sub-basins	Year data	Precipitation				Runoff				R^2
		Change (%)	Change (mm)	z-statistic	Confidence (%)	Change (%)	Change (mm)	z-statistic	Confidence (%)	
Upper1	1956–2000	4.8	31	1.03	NS	6.4	18	0.89	NS	0.59
Upper2	1956–2000	−11.0	−116	−2.59	99.5	−12.9	−70	−1.44	90	0.49
North	1951–2000	−2.5	−24	−0.35	NS	−25.7	−100	−1.86	95	0.47
South	1956–2000	7.8	106	1.54	90	18.6	134	1.95	95	0.82
Above-Datong	1951–2000	−1.0	−11	−0.03	NS	2.4	13	1.02	NS	0.83

R^2 is the correlation coefficient between precipitation and runoff. NS, not significant.

Sediment

Over the past 56 years, annual sediment discharges in all parts of the Yangtze Basin have been varied considerably more than water discharges, and have declined markedly since the 1980s (Figure 29.7b). As a result of several major declines (discussed below), annual discharges from upper (as measured at Yichang) and lower (as measured at Datong) reaches during the 2003–2005 period after the closure of TGD were 90 and 190 mt, respectively, only 17% and 38% of their 1950–1960s averages (Figure 29.7b).

Sediment discharges from all 23 stations, located on the mainstem or tributaries, have decreased except for some minor increases along a few south-eastern tributaries (Figure 29.8). Decreases have been most striking (>80%)
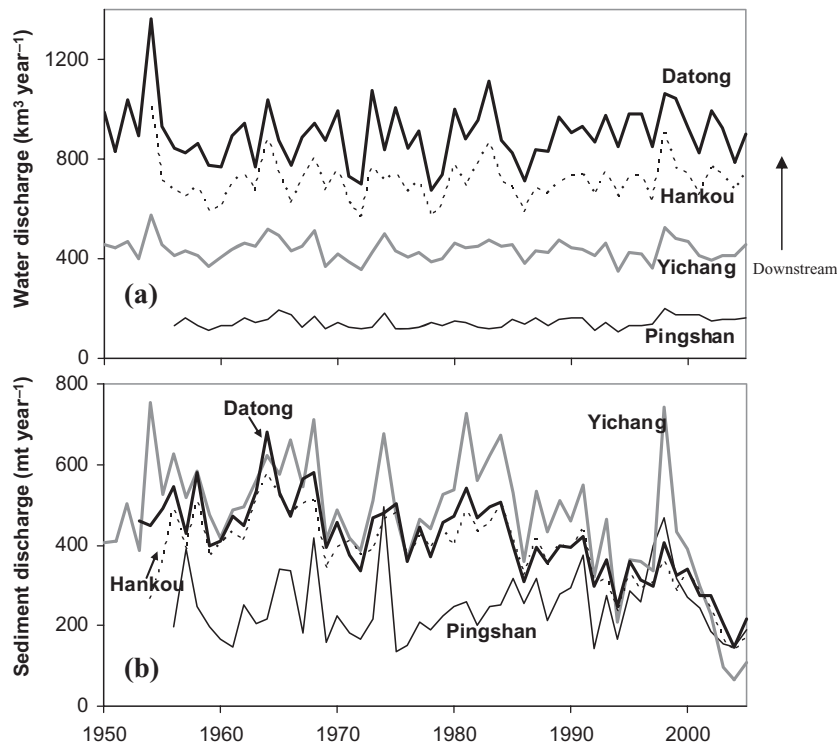
Figure 29.7 Temporal variations of water discharge (a) and sediment discharge (b) in upper (Pingshan and Yichang), middle (Hankou) and lower (Datong) reaches of the mainstem Yangtze River, 1950–2005

for the two northern tributaries (Jialing and Han) as well as the two passages between the Yangtze mainstem and Dongting Lake (Figure 29.1). Unlike the sharp decreases noted for the Jialing (in 1986) and Han (in 1968) tributaries, declines at the two passages have been more gradual (Figure 29.8). Sediment discharges along the tributaries have decreased in general along the mainstem of the Yangtze. An 80-mt sediment reduction in 1968 at the Han River in the north (Figure 29.8, marked 1) correlates well with (and was partially caused by) decreased discharge at Datong at that time. A 100-mt decrease in the sediment discharge of the Jialing in 1986 (Figure 29.8, marked 2) and the impoundment of TGD in 2003 (Figure 29.8, marked 3) both led to corresponding drops at Yichang and Datong.

29.5.2 Monthly variations

The aforementioned variations can be shown in more detail at the monthly scale. Under a monsoon regime, the monthly water and sediment discharges in the Yangtze display a strong seasonal pattern, about 70 % of water and

85 % of sediment being discharged between May and October in upper (Yichang), middle (Hankou) and lower (Datong) reaches (Figure 29.9). Although both show uni-modal patterns, variations in water discharge are less seasonal than those of sediment load; low water discharge in January generally is around 20 % of the peak water discharge in July whereas January sediment discharge is <3 % of that in July (Figure 29.9).

From 1950 to 2005, the annual pattern of monthly water discharge showed small changes from upper reaches to lower reaches (Figure 29.9a), similar to minor variations in annual values (Figure 29.7a). In order to delineate detailed changes in seasonality, we compared 5-year mean monthly water discharges for a period before many dams have been built (1955–1959) with the period 2001–2005 when >50 000 dams have been in operation in the basin. During this interval, the flood-season (July–August) water discharge decreased slightly at Yichang (presumably because of the TGD impoundment) but changed little downstream at Hankou or Datong (Figure 29.9a). The dry-season (January–February) monthly discharge, however, increased by about 40 % at Datong, probably
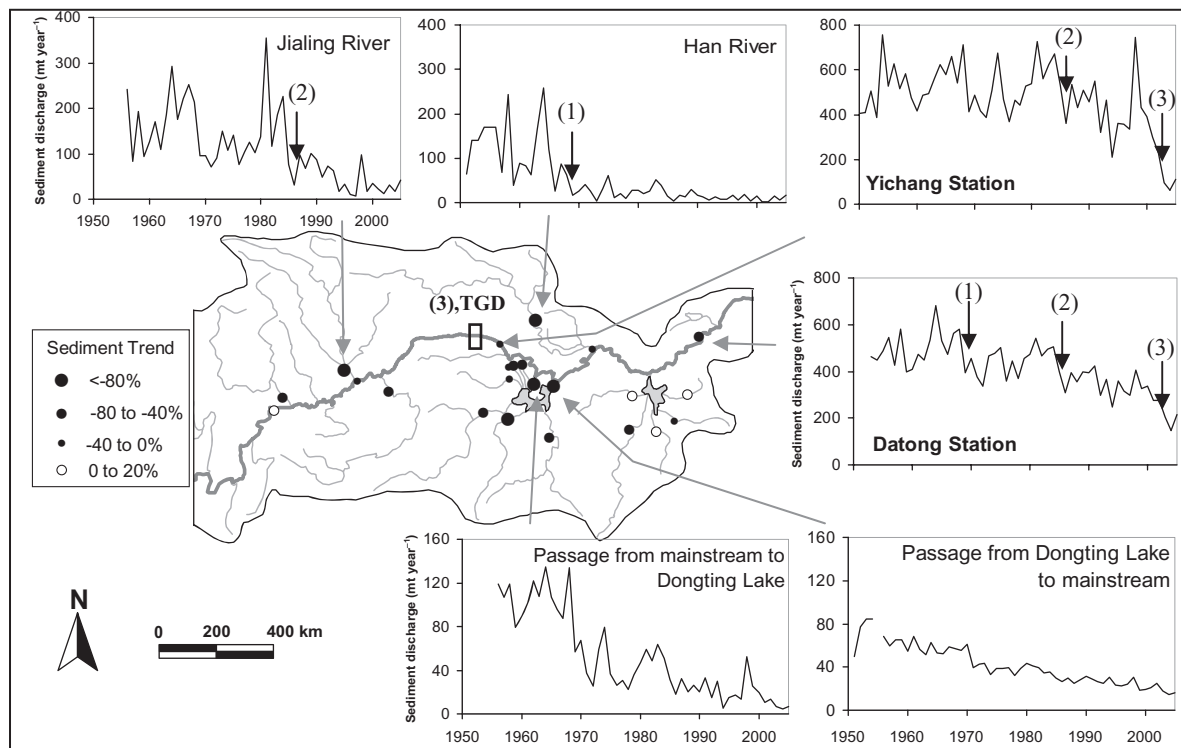
Figure 29.8   Temporal sediment variations at four stations in which sediment discharge decreased more than 80%. Also shown are variations at Yichang and Datong on the mainstem as well as sediment trends from 1950 to 2005 at 23 stations. Gauging stations for the Jialing and Han Rivers and two passages are Beibei, Huangzhuang, Ouchiguan and Chenglingji, respectively. See Figure 29.11 for Dongting Lake details

reflecting a change in seasonal precipitation or winter release of water stored in the reservoirs upstream of dams.

Monthly sediment discharges have changed much more dramatically than water discharges. Except for minor decreases in August discharges, monthly sediment discharges remained more or less constant along the Yangtze from 1950 to 1985 (Figure 29.9b). Subsequently discharges declined moderately between 1986 and 2002, and dramatically after 2003 (Figure 29.9b). Peak sediment discharges during July–August in 2003–2005 at Yichang, Hankou and Datong were only 17%, 33% and 36% of their discharges in 1950–1967 respectively (Figure 29.9), thereby reflecting a damped downstream signal as well as channel erosion downstream of the TGD (Xu *et al*., 2006). About 100–150 mt of sediment have been trapped in the reservoir upstream of the TGD annually between 2003 and 2005, and more than 70% of that occurred between June and September (Bulletin of Yangtze Sediment, 2000–2005).

29.6 DISCUSSION – CLIMATIC AND ANTHROPOGENIC IMPACTS

Temporal variations in water and sediment discharges in the Yangtze Basin have been controlled by various forcings: climatic (precipitation and evapotranspiration) and anthropogenic (water diversions, dam construction and lake reclamation).

29.6.1 Climatic impacts

As shown in Figures 29.5 and 29.6, local precipitation and runoff in the Yangtze drainage basin changed considerably between 1951 and 2000, although basin-wide values changed little. Increases in the south-east (sub-basin South) and decreases in the north (sub-basin North) have been especially striking. In a natural hydrological regime, runoff is the difference between precipitation and the sum of evapotranspiration and storage. In a heavily human-
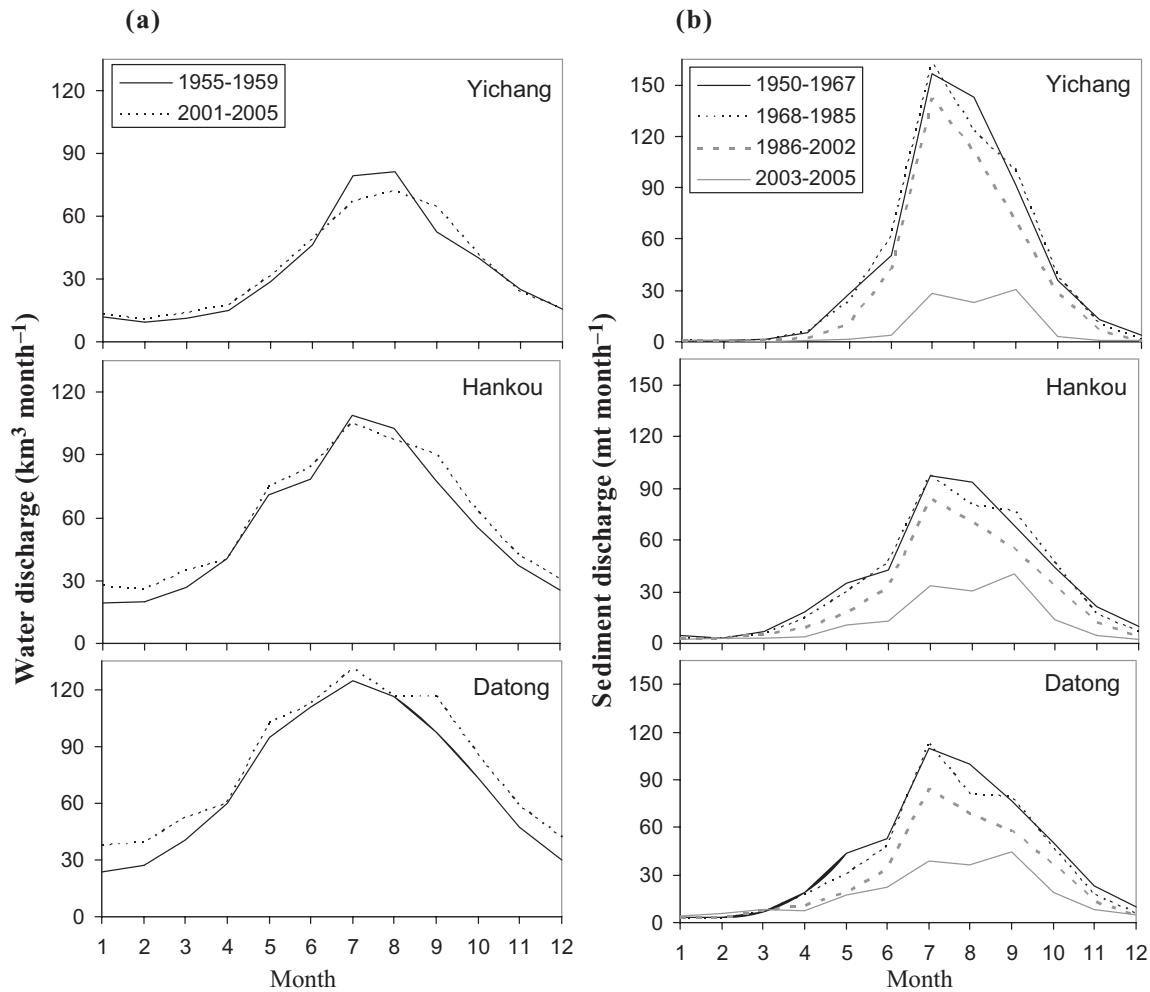
(a)

(b)

Figure 29.9 Changes in monthly water discharge (a) and sediment discharge (b) in upper (Yichang), middle (Hankou) and lower (Datong) reaches of the Yangtze River, 1950–2005. Note that Yichang and Hankou Stations lack the 2000 figures and Datong that of 1970, 1971, 1974 and 1975

impacted basin like the Yangtze, water consumption, the withdrawn water directly lost to the basin, also must be taken into account. As water storages as groundwater and in reservoirs are small relative to precipitation and runoff throughout the watershed (Xu, 2006), the runoff of the Yangtze should mainly reflect the difference between precipitation and the sum of evapotranspiration and water consumption.

Runoff in the sub-basin South (Figure 29.6, Table 29.1) increased (18.6%, 134 mm, 95% confidence interval) more than precipitation (7.8%, 106 mm, 90% confidence interval). As there is no evidence of decreased water con-

sumption (which actually may have increased) the increased runoff more likely reflects decreased evapotranspiration. This conclusion generally agrees with both measured pan evaporation (Liu *et al*., 2004) and calculated potential evapotranspiration (Thomas, 2000). From 1955 to 2000, pan evaporation decreased significantly in south-eastern China (near sub-basin South) mainly due to decreasing solar irradiance (Liu *et al*., 2004). From 1954 to 1993, potential evapotranspiration also decreased in southern China (south of 35°N) where sunshine appears to play a key role in evapotranspiration (Thomas, 2000). Therefore, decreased evapotranspiration in sub-basin South of the

Yangtze might be explained by decreased sunshine, increased atmospheric haze (Roderick and Farquhar, 2002), decreased plant transpiration owing to stomatal closure in response to increased atmospheric CO_2 levels (Gedney *et al*., 2006), or a combination of all three.

In the sub-basin North (Figure 29.6), however, runoff decrease (−25.7%, −100 mm) was about four times of the decline in precipitation (−2.5%, −24 mm). Since we find no proof of increased evapotranspiration, this decreased runoff in sub-basin North was probably caused by increased water consumption, similar to the situation in the basin of the Yellow River to the north (Wang *et al*., 2006).

Precipitation also plays a key role in eroding and transporting sediment within the Yangtze drainage basin, par-

ticularly in the upper reaches (Ma *et al*., 2002; Zhang and Wen, 2002). Lying in an area of high sediment yield (>500 t km^{-2} $year^{-1}$) drained by the Jialing and Min tributaries (Figure 29.5), sub-basin Upper2 experienced the greatest decrease in precipitation between 1951 and 2000 (−11.0%, Figure 29.6), to which both runoff ($R^2 = 0.56$, Figure 29.10a) and sediment discharges (until 1985; $R^2 = 0.51$, Figure 29.10b) responded accordingly. Although precipitation has remained relatively steady since 1986, the measured sediment discharge in sub-basin Upper2 has declined dramatically (bold black line, Figure 29.10c). Based on the 1956–1985 runoff-sediment correlation (Figure 29.10b), calculated post-1986 sediment discharges (bold grey line, Figure 29.10c) were significantly higher than those actually measured. Therefore, decreased pre-
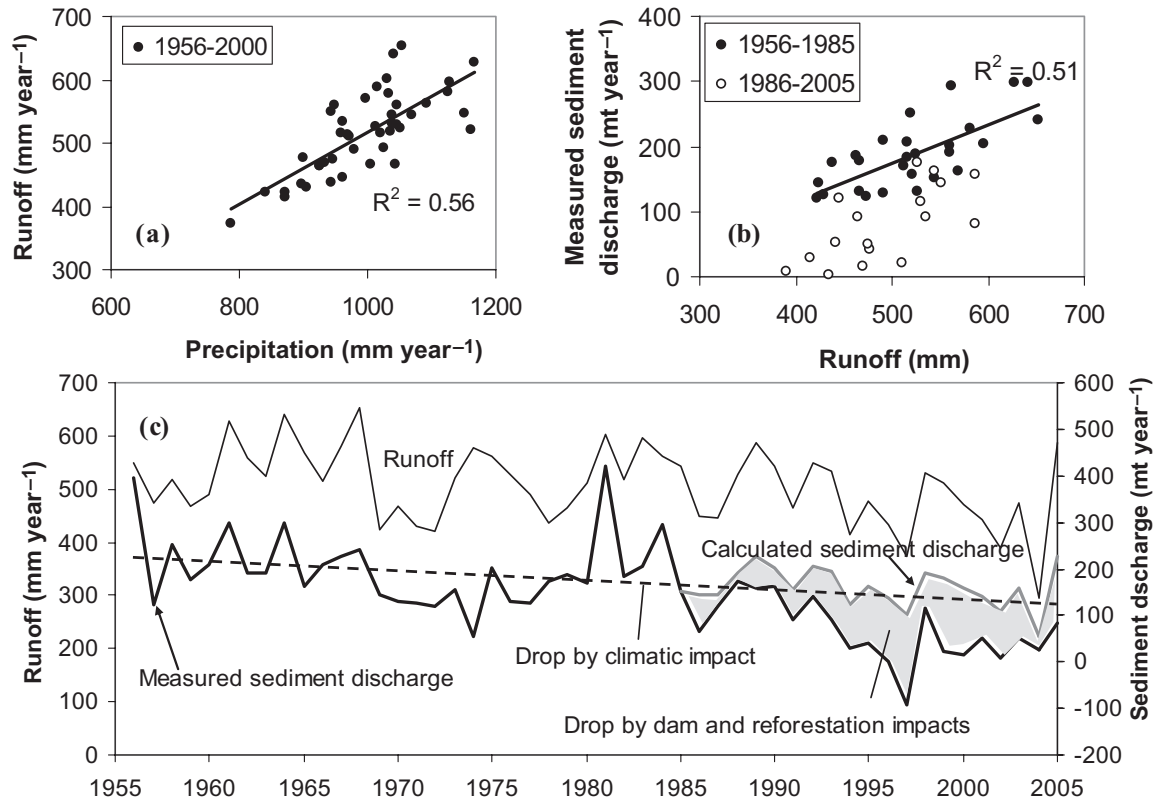

Figure 29.10　Precipitation, runoff and sediment discharge between Pingshan and Cuntan gauging stations (Sub-basin Upper2, Figure 29.6). Runoff and sediment discharge are determined by subtracting discharge of Pingshan from that of Cuntan. Correlation analysis of 1956–2000 in (a) excludes 1986 owing to extensive dam impoundments. In (b), the 1956–1985 runoff-sediment correlation excludes three abnormal years (1956, 1974 and 1981). In (c), the negative measured discharge of 1997 probably indicates channel siltation. The dashed trend line indicates the sediment drop due to decreased precipitation, and the difference (grey region) between measured and calculated sediment (derived from b) in 1986–2005 is mainly caused by anthropogenic activities, such as dam construction and reforestation

cipitation and runoff have caused about 80 mt decrease in sediment discharge from 1956 to 2005 (dashed line for 'climatic impact', Figure 29.10c). However, the difference between the calculated and measured discharges between 1986 and 2005 (grey region, Figure 29.10c) can be regarded as sediment decline due to human activities, such as reforestation and dam construction.

29.6.2 Anthropogenic impacts

Because anthropogenic activities and climate change synchronize with respect to both space and time, it is difficult to separate their impacts on the Yangtze Basin quantitatively (Higgitt and Lu, 1996; Yang *et al*., 2002; Li *et al*., 2004; Zhang and Wen, 2004; Yang *et al*., 2005). In general, deforestation and agriculture increase the sediment discharge (Dai and Tan, 1996), but they can be counteracted by dam construction, water diversion, lake reclamation and reforestation. Three major types of anthropogenic activities are discussed below.

Dam construction

The number of dams in the Yangtze Basin has increased dramatically from only a few in the 1950s to more than 50 000 at present. Dams have played a key role in reducing sediment transport throughout the entire Yangtze drainage basin. On the Han River, Danjiangkou Dam decreased sediment sharply in 1968, as its reservoir had a trapping efficiency greater than 95% (Figure 29.8, 1). Sediment decrease in the Jialing (Figure 29.8, 2) in sub-basin Upper2, was initiated by a decrease in precipitation in 1986 (Figure 29.5), but more importantly, by construction of about 12 000 dams and extensive watershed reforestation in its basin. These activities have trapped about 100 mt year^{-1} since 1986 (EGRSTGP, 2002). Since the beginning of the impoundment upstream of the TGD in 2003, about 150 mt year^{-1} of sediment discharge has been reduced in both the upper (Yichang) and lower (Datong) reaches of the river (Figure 29.8, 3).

Water consumption

Withdrawal and consumption of water has occurred concurrently with dam construction in the Yangtze Basin. From 1949 to 2000, Yangtze water withdrawal increased rapidly in response to increased irrigation for agriculture and demand for an expanded population from about 180 to >400 million. Over the same period, water consumption also increased from 15 to 90 km^3 year^{-1} (Bulletin of Water Resources in China, 1997–2005; Heilig, 1999). The present pattern of Yangtze Dam impoundments and water

diversion, however, appears to have had relatively small impact on annual and monthly water discharges (Figures 29.7a and 29.9a), even though the Yangtze is a highly impacted river in terms of fragmentation and flow regulation (Nilsson *et al*., 2005).

That the Yangtze's water discharge has not changed significantly over the past 56 years is explained mainly by the sheer magnitude of the basin area and the high volume of discharge – fifth largest in the world. Even with a sixfold increase in water consumption since 1950, a figure of 90 km^3 year^{-1} represents only 10% of its annual discharge. Although by 1995 more than 46 000 dams had been constructed in the basin and their total water-storage capacity had reached 142 km^3 (Yang *et al*., 2005), the volume of annual stored water in the reservoirs upstream of dams was less than 10 km^3, about 1% of the annual discharge (Bulletin of Water Resources in China, 1997–2005). Even the TGD impoundment in 2003 only trapped about 17 km^3 water, 2% of the annual discharge of the Yangtze. The total capacity of TGD will be 39 km^3 in 2009 when the TGD is in full operation, thereby impounding 5% of the annual discharge of the Yangtze to the coastal region. In 2003, this TGD impoundment caused moderate declines of discharge upstream at Yichang only in July and August, underscoring the modulating capacity of a high-discharge river like the Yangtze.

Lake reclamation

Many lakes occur in the Yangtze Basin, including Dongting Lake located in the middle reaches. This major lake receives discharges both from mainstem passages (labelled 1–5, Figure 29.11a) and southern tributaries (labelled 6–9), the water then flows back to the Yangtze mainstem at Chenglingji Station (Figure 29.11a). Historically Dongting Lake has supplied freshwater to tens of millions of inhabitants and buffered the impact of floods in the middle reaches.

Since the 1950s, however, extensive reclamation, together with siltation, have led to a rapidly declining lake area (Shi *et al*., 1985; Du *et al*., 2001), from 4350 km^2 in 1949 to 2623 km^2 in 1995 (Bulletin of Yangtze River Sediment, 2000–2005). Since 1956, both water and sediment flowing in and out of Dongting Lake have declined. The differences between the sediment discharges measured in the five passages draining from mainstem to Dongting Lake and those measured as the return flow at Chenglingji, indicate that less and less net sediment has escaped from the mainstem (Figure 29.11b). Similarly, an input–output sediment budget for Dongting Lake (1–9, Chenglingji) shows that net trapped sediment into the lake also has declined sharply (solid line, Figure 29.11b). In the 1950s,
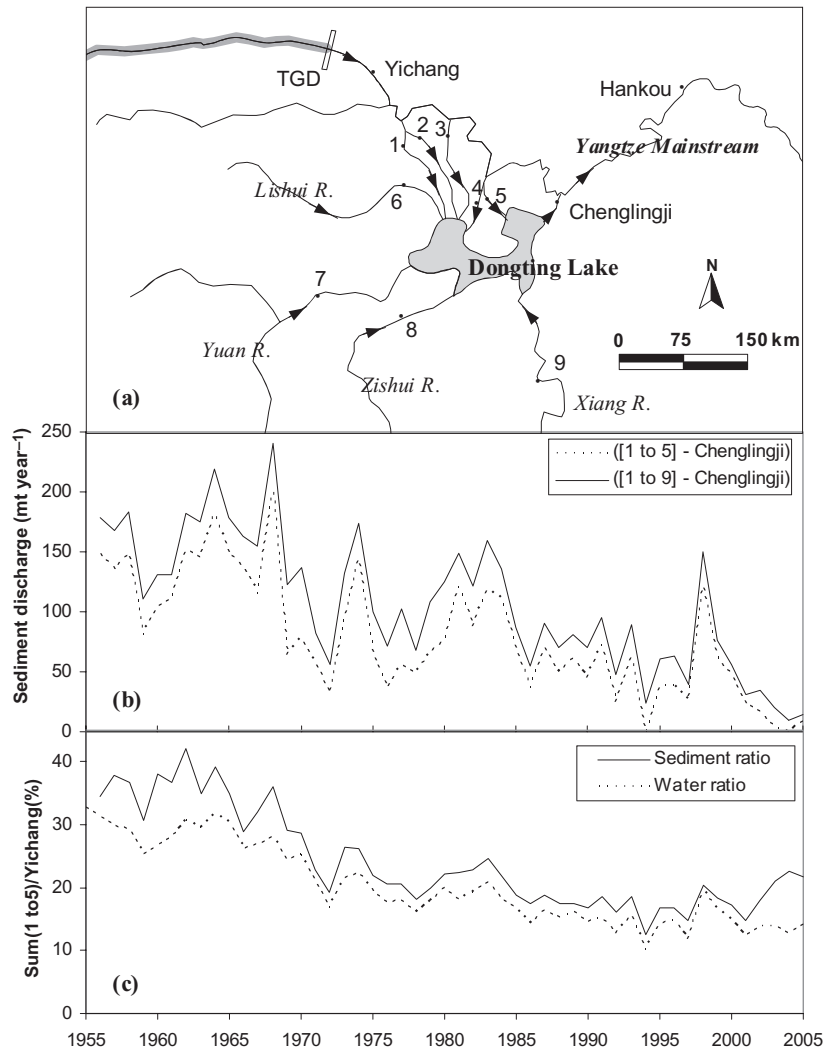
Figure 29.11 (a) The passages and tributaries connecting to Dongting Lake as well as their gauging stations: 1, Xinjiangkou; 2, Shadaoguan; 3, Taipingkou; 4, Ouchikang; 5, Ouchiguan; 6, Shimen; 7, Taoyuan; 8, Taojiang; 9, Xiangtan. The broad grey line upstream of the TGD (Three Gorges Dam) represents the impounded channel. (b) Sediment trapped in Dongting Lake. Dashed line is the difference between sediment discharged into the lake from Yangtze mainstem (as measured at stations 1–5) minus sediment discharged from the lake back into mainstem (as measured at Chenglingji). Solid line adds the inputs from four southern tributaries to Lake Budget. (c) Water and sediment passing into Dongting Lake from Yangtze mainstem, expressed as proportions of the total water and sediment passing Yichang

the five passages transported 35% of water and sediment passing Yichang Station, but in recent years they have carried only 15% of these from Yichang (Figure 29.11c), indicating Dongting's declining role in flood modulation. Since the construction of the TGD led to active channel erosion downstream of Yichang after 2003 (Xu *et al*., 2006), scouring has taken place in the mainstem channel, probably further decreasing discharge into the lake, as forecasted by Zhang (1995). Although the TGD can buffer the flood water arriving from the upper reaches, the four high-runoff southern tributaries (Figure 29.3) can discharge massive quantities of water directly into the shrinking Dongting Lake, thereby causing an unsolved serious flood problem for the middle Yangtze. The extended sur-

vival of the Dongting Lake, the major freshwater source in the middle reaches of the Yangtze, has become a serious problem.

29.7 FUTURE CHANGE AND COASTAL RESPONSES

29.7.1 Water discharge

Over the past 56 years, water consumption within the Yangtze River basin has represented fairly small proportions of its total water discharge. The South–North Water Diversion Project of the future, however, is scheduled to transfer freshwater from the humid southern China, mainly from the Yangtze, to the dry northern China, including the Yellow River (Figure 29.1). This will take place through three passages termed East, Middle and West (Chen *et al*., 2003). The reservoir upstream of the Danjiangkou Dam on the Han tributary will be one of the major freshwater sources of the Middle Passage, delivering water directly to Beijing. This diversion will certainly diminish further both water and sediment discharges of the Han tributary in the northern Yangtze. Although only 5% (45 km^3 year^{-1}) of the Yangtze annual water discharge will be diverted (Chen, X. *et al*., 2001), this anthropogenic transfer may fundamentally change the Yangtze water cycle since most of the diverted water will be removed from the Yangtze drainage basin.

29.7.2 Sediment load

Sediment discharge at Datong (the seaward-most station, 600 km from the river mouth) has declined to 140 mt from a mean level of 480 mt year^{-1} in the 1950–1960s, since the TGD impoundment (Figure 29.7). Both Yang *et al*. (2002) and Yang, Z.S. *et al*. (2006) forecasted the volume of the future sediment passing Datong in the next half century. It is difficult, however, to extend their predictions to the amount of sediment that would enter the East China Sea owing to various ongoing and future impacts as detailed below.

First, we need to understand the impact of ongoing and proposed upstream dam construction. Except for the Gezhouba, no dams had been constructed on the mainstem of the Yangtze before the TGD in 2003. In the next two decades, however, China is going to build four large dams (Wudongde, Baihetan, Xiluodu and Xiangjiaba) on the Yangtze upstream of the TGD where sediment yield is extremely high (Figure 29.5). These four dams would add an additional 41 km^3 of total water-storage capacity, and their total installed hydropower capacity would be 38 500 MW, about double that of the TGD. One of the

objectives of these four planned dams is to prolong the useful life of the TGD by trapping the sediment that otherwise would fill its reservoir. However, the impact of these dams has not been figured into the two predictions mentioned earlier (Yang *et al*., 2002; Yang, Z.S. *et al*., 2006).

Second, sediment trapping in Dongting Lake has decreased from 180 mt in the 1950s to nearly zero at present (solid line, Figure 29.11b). This decline has fundamentally changed the sediment correlation between Yichang and Datong, the major sites used for two predictions. Third, channel erosion downstream of dams may counteract the trapping of sediment by the reservoir to some extent. Channel erosion has already occurred downstream of the TGD (Xu *et al*., 2006), and will surely happen downstream of four planned dams. Last, little is known regarding the ungauged section from Datong 600 km downstream to the river mouth. Many uncertainties remain concerning the possible response (erosion and resuspension) of this last downstream reach to the cessation of sediment from the upper river.

29.7.3 Coastal responses

The sediment threshold at Datong that is required to sustain the geometry of modern Yangtze Delta was estimated to be 263 mt year^{-1} (Yang *et al*., 2005). The sediment discharge, however, has been below this level since 2000 (Figure 29.7). Given dam construction of the future, decreased erosion in response to ongoing conservancy in the basin, and diversions of water, sediment discharge of the Yangtze most likely will continue to decline, impacting the delta and coastal region.

Accretion in the Yangtze subaqueous delta has slowed down and erosion has occurred on the outer side of the Yangtze Delta front (Yang *et al*., 2002). Coastal wetland located in the eastern part of the Yangtze Delta stopped prograding in the past decade and began to recede; wetlands above the 0-m isobath decreased by 19% between 2001 and 2004 (Yang, S.L. *et al*., 2006). Delta subsidence, shoreline retreat, erosion of seawalls, and other subsequential problems may concur with wetland loss. All these may create serious problems in Shanghai, the most populous city in China with about 20 million inhabitants.

The Yangtze River provides a substantive amount of nutrients, nourishing rich fishing grounds on the inner continental shelf of the East China Sea. A decline of sediment supply also reduces the supply of nutrients, particularly silicates. For instance, between 1998 and 2003, the Si : N ratios dropped from 1.5 to 0.6 and primary production decreased by 86% in the East China Sea (Gong *et al*., 2006). Due to Si-limitation, the phytoplankton community has shifted from diatom-dominated to flagellate-

dominated, thereby changing the ecological communities (Gong *et al*., 2006). After the TGD impoundment in June 2003, saltwater intrusion in the Yangtze Estuary appeared earlier and its duration lengthened (Xian *et al*., 2005). This saltwater intrusion has led to increased water temperature and salinity, which consequently stimulated several jelly-fish blooms in the estuary in 2003 and 2004 (Xian *et al*., 2005). Since jellyfish can feed on fish eggs and larvae, these jellyfish blooms may also endanger coastal fishing resources.

29.8 CLIMATIC AND ANTHROPOGENIC IMPACTS ON OTHER GLOBAL RIVERS – THE MISSISSIPPI EXAMPLE

Owing to their inability to modulate basin-wide change, rivers draining small basins are generally more responsive to both sudden and long-term changes. Similarly, arid basins are more likely to feel the effects of climatic and anthropogenic change than rivers draining humid basins. For example, present-day runoff from the Yellow River is only about 15 % of its 1950s levels owing to decreased precipitation and, more importantly, increased water con-sumption (Wang *et al*., 2006). Similarly, the impoundment by the Aswan High Dam and related downstream irriga-tion have decreased the Nile's water and sediment dis-charge to less than 10 % of the pre-Aswan levels.

While low-runoff rivers seem more vulnerable to cli-matic and anthropogenic changes, high-runoff rivers also can be affected, as shown by the Yangtze in the present chapter. Another obvious example is the Mississippi River. While its drainage basin is nearly twice as large as the Yangtze's (3.3 vs 1.8×10^6 km^2), its pre-dam annual water and sediment discharges were not dissimilar (650 km^3 and 500 mt) to those of the Yangtze (900 km^3 and 480 mt). Moreover, both rivers are joined by high-runoff, low-sediment-yield tributaries in the south and east (the south-ern rivers in the Yangtze, and the Ohio-Tennessee in the Mississippi), and low-runoff, high-sediment-yield tribu-taries in the north-west and west (the northern and upstream rivers in the Yangtze, and the Missouri-Arkansas in the Mississippi) (Figure 29.12). The low-runoff Mis-souri and Arkansas occupy a larger percentage of the Mis-sissippi drainage basin than do the north-western rivers in the Yangtze Basin, leading to a substantially lower runoff to the coastal waters.

Dam construction on the Mississippi accelerated in the 1930s for better navigation, flood control, and generation of hydroelectric power as well as in response to economic depression, much in the same way as it did on the Yangtze Basin after 1950. As with the Yangtze, Mississippi water discharge has not decreased despite the more than 50 000

dams throughout its watershed. In fact, between 1950 and 2000, discharge increased about 30 % (Figure 29.13) in response to the Pacific Decadal Oscillation and the North Atlantic Oscillation (Hurrell, 1997; Lins and Slack, 1999). Despite the increased water discharge, however, sediment delivery of the Mississippi has decreased by about 75 % since the early 1950s (Figure 29.13). Unlike the Yangtze, which has experienced several distinct episodes of decreased sediment delivery in response to climatic and land-use changes, however, the sharply decreased sedi-ment discharge from the Lower Mississippi reflects pri-marily the construction of the Fort Randall and Gavins Point Dams in 1953 and the Garrison Dam in 1954 along the middle reaches of the Missouri River (Meade and Parker, 1985). Sediment delivery since the mid-1950s has shown only a slight decline even though dams have con-tinued to be built (Figure 29.13).

Another impact from dam construction, combined perhaps with climate change, has been the change in sea-sonality of water discharges from both the Mississippi and Yangtze. Water discharges during high-flow months in both rivers have decreased in company with increased discharges during low-flow months (Figure 29.13). Although changes in seasonal precipitation may partially explain these variations, more likely are the releases of stored water from upstream reservoirs in response to hydroelectric and irrigation needs.

As with many other North American and European rivers, it seems doubtful that other large dams will be built on the Mississippi, at least in the foreseeable future; as such any significant change in Mississippi sediment dis-charge is likely to reflect landuse change rather than the river flow. By contrast, the number of large dams still planned for the Yangtze suggests that sediment delivery will continue to decline in the coming years in response to both changes in river flow and landuse.

29.9 CONCLUSIONS

From 1950 to 2005, construction of over 50 000 dams and consumption of 90 km^3 water have led to small variations in annual and monthly basin-wide water discharges from the Yangtze River. Regionally, runoff in the Yangtze north-ern sub-basin has declined much more than has preci-pitation owing to increased water consumption, whereas increased runoff in the southern Yangtze may reflect decreased evapotranspiration. Since the 1980s, however, Yangtze sediment discharge has decreased dramatically. In 2003–2005, the upper river (measured at Yichang) and lower reaches (Datong) transported only 17 % and 38 % of their natural sediment discharges in the 1950–1960s, respectively. Throughout the basin, the most striking sedi-
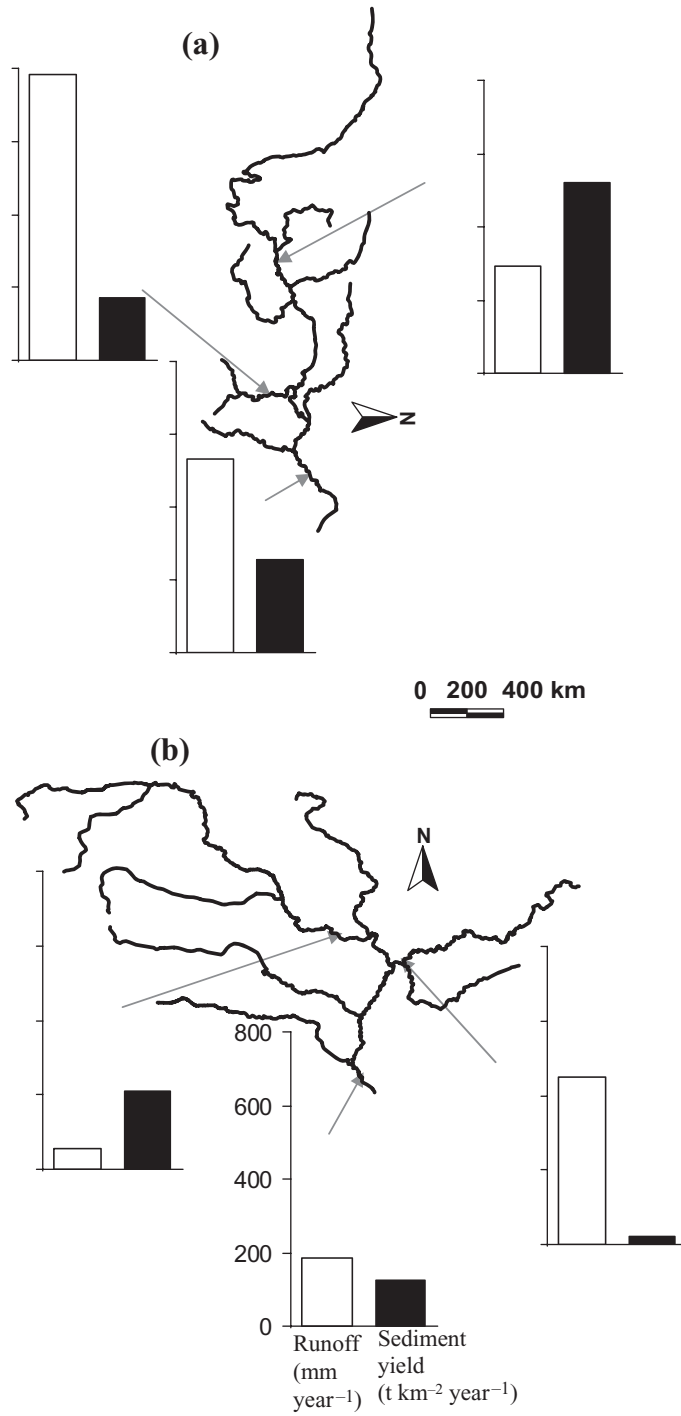
Figure 29.12 Spatial distribution of runoff and sediment yield in the (a) Yangtze and (b) Mississippi Rivers. Both rivers are characterized by high-runoff, low-sediment-yield tributaries to the south and east, respectively, counterbalanced by low-runoff, high-sediment-yield tributaries to the north-west and west
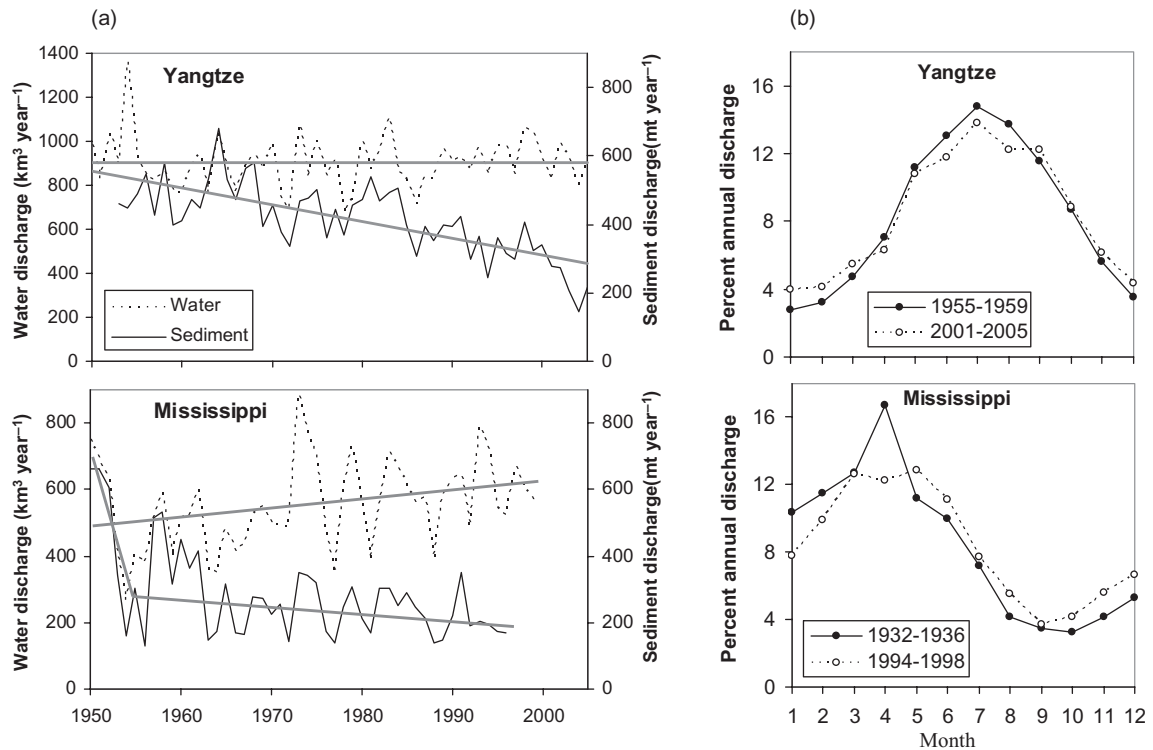
Figure 29.13 (a) 1950–2005 trends of water and sediment discharges from the lower reaches of the Yangtze and Mississippi Rivers. The Yangtze has experienced a small variation in water discharge but a gradual decrease in sediment discharge since 1986. In contrast, the Mississippi has experienced a 30% increase in water but a sharp decline in sediment after construction of three Missouri River dams in the early 1950s. (b) Monthly water discharges from the Yangtze and Mississippi Rivers during early and recent 5-year periods. Decreased water discharges during high-flow months and corresponding increased discharges during low-flow months may reflect changes in seasonality of precipitation and/or the release of reservoir-stored water for hydropower and irrigation during low-flow months

ment decreases (>80%) occurred in the Jialing and Han tributaries (mainly owing to dam construction), as well as in the two passages between the mainstem and Dongting Lake (owing to lake reclamation). The shrinking Dongting Lake now carries a much smaller percentage of the discharges passing Yichang increasing the flood potential of the middle Yangtze. Given the proposed increase in the number of major dams and water diversions, sediment discharge from the Yangtze will probably continue to decline such that Yangtze delta and coastal areas could be severely impacted.

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