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Gender of large river deltas and parasitizing rivers

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Abstract

Deltas are the most dynamic part of large rivers and the characteristics of deltas reflect the basic nature of morphodynamics, ecology and anthropogenic influence. The authors investigated many deltas of large rivers, including the Yellow, Yangtze, Pearl, Rhine, Nile, Mississippi, Luanhe and Ebro rivers. Data were collected and sediment, water, benthic invertebrates and fish were sampled. Statistical analysis showed that deltas can be classified into male deltas and female deltas. The deltas of the Yellow, Mississippi, Luanhe, Ural and Ebro rivers are male deltas. Male deltas extend into the ocean, each with only one or two channels, forming a fan-shape. Its development process is accompanied with periodic nodal or random avulsions. Male deltas develop if the sediment load/water ratio is high and the tidal range is low. The deltas of the Yangtze, Rhein-Meuse-Scheldt, Pearl and Irrawaddy rivers are female. Female deltas consist of complex channel networks and numerous bars and islands. Female deltas develop if the load/water ratio is not high and tidal current is relatively strong. Female deltas provide stable and multiple habitats for various bio-communities. Therefore, the biodiversity of female deltas and the taxa richness of benthic invertebrates and fish are much higher than that of male deltas. Human activities reduced sediment load and change the delta gender from male to female. Male rivers have high levees in their lower reaches and estuary. Several rivers originate from the levees of a male river and flow parallel with the river into the sea. Appearance, persistence, length and stability of these rivers depend on the male river to which they are attached. Therefore, these rivers are named parasitizing rivers. In general, parasitizing rivers have no tributaries and almost no drainage area. The runoff of these rivers comes from the rainfall on the surrounding area, and therefore, the flow discharge exhibits very sharp peaks during rainfall. The Yellow and Luanhe rivers have many parasitizing rivers. Some of the parasitizing rivers are quite long, with a length of 400-500 km, such as the Tuhai River and Majia River. Management of parasitizing rivers must be integrated into management strategies of their father rivers.

Key Words: Classification of deltas, Male and female rivers, Morphology, River patterns, Parasitizing river, Yellow River

1 Introduction

A great river can carry sediment eroded from mountainous areas long distances to its respective river mouth. As a consequence land is created at the river mouth. A delta develops if a river carries a high sediment load, e.g. where the load/water ratio exceeds 0.2 kg/m^3 (Friedman and Sanders, 1978). Most rivers in China carry high sediment loads, and therefore develop deltas. The developmental processes

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associated with deltas depend primarily on the water discharge, sediment load, tidal currents and waves, surrounding coastal sediments, and human activities.

The architecture of deltaic systems is affected by the interacting dynamic processes of climate, hydrology, wave and tidal action, which sort and disperse sediment (Coleman, 1982). These processes, which vary in both intensity and frequency, control the eventual sedimentary framework of a delta (Coleman and Wright, 1973; Orton and Reading, 1993; Overeem et al., 2005). Many classification schemes have been used to organize the morphology of deltas through an understanding of sediment-transport dynamics (Syvitski and Saito, 2007). The processes of delta development depend largely on the ratio of sediment supply to sediment retention. Friedman and Sanders (1978) classified the morphology of the mouth of large rivers, according to concentration of suspended sediment load, as estuaries (<0.16 kg/m^3), deltas (>0.2 kg/m^3), and a transitional group (0.16-0.2 kg/m^3), based on data from 29 large rivers mouths across the world. The most cited classification scheme of deltas was introduced by Galloway (1975), where three main types of deltas were distinguished according to the dominant forces of the formation process: river-, wave-, and tide- dominated deltas. Mcpherson et al. (1987) classified deltas into different fan deltas according to their geomorphic and sedimentologic settings. Fan deltas are gravel-rich deltas formed where an alluvial fan is deposited directly into a standing body of water from an adjacent highland; and braided deltas are gravel-rich deltas that form where a braided fluvial system protrudes into a standing body of water. Factors affect deltaic processes include sediment load and grain size, quantitative wave and tide (Orton and Reading, 1993), sea-level variation (Dalrymple et al., 1992; Postma, 1995), and human activities (cannals, levees, dams, water diversion, etc), and these factors may vary in time and space (Correggiari et al., 2005).

Human activities affect the growth and evolution of deltas (Syvitski et al., 2005; Syvitski et al., 2009; Rao et al., 2010), since the sediment load (and size distributions) and flow discharge to the lower reaches of most rivers have been markedly intervened by dams, levees, water diversion, and reforestation. Other factors, such as sea level and tidal currents have little variation in a short or medium time scale. Human activities strongly influence the sediment flux and cause drastic variation to many rivers, which in turn impacts deltaic processes. The amount, mode of transport, and grain size of the sediment load delivered to a delta front affect the facies, formative physical processes, related depositional environments and morphology of the deltaic depositional system (Orton and Reading, 1993; Syvitski and Saito, 2007).

With the ever-increasing intensity of human influences and global climate change, many deltas can be expected to shrink, some already have. More and more deltas are moving away from their historical equilibrium between sediment supply and sediment dispersal. The reduction in sediment delivery to deltas due to sediment trapping behind dams, along with the practice of routing river discharge across delta plains, contributes to the shrinking of world deltas. Consequences include shoreline erosion, threatened mangroves swamps and wetlands (Boesch et al., 1994; Britsch and Dunbar, 1993, 1996), increased salinization of cultivated land, and risk of tidal surges (Syvitski, 2008).

Large rivers (with a length longer than 1,000 km) carry no gravel to their mouths and their deltas are formed from sand, silt and clay. The gradient of these rivers in their estuarine reaches are mostly about or less than 0.01%. The areas of their deltas are very large, generally from several tens to several tens of thousands square kilometers. The classification of large river deltas is different from that of small rivers. The authors investigated many deltas of large rivers, including the Yellow, Yangtze, Pearl, Rhine, Nile, Mississippi, Luanhe and Ebro rivers from 2003 to 2010. Data were collected and sediment, water, benthic invertebrates and fish were sampled. The dynamic, morphologic and ecological characteristics of the deltas were studied. The results showed that deltas can be classified into male deltas and female deltas. In general, male deltas are not stable and have only one or two channels, such as the Yellow River delta. Female deltas consist of complex channel network and numerous islands, which are relatively stable. The Yangtze River delta is a typical female delta. Rivers have male or female deltas are male and female rivers, respectively.

Large male rivers have high levees in their lower reaches and estuary. Many smaller rivers originate from the levees of male rivers and flow parallel with the river into the sea. These smaller rivers depend on the stability of their father river. Therefore, these smaller rivers are named parasitizing rivers. The Yellow and the Luanhe rivers have many parasitizing rivers. Different from other river patterns the parasitizing rivers have no (or very few) tributaries, no upstream reaches, and very narrow drainage area. The hydrograph of these rivers is unique depending mainly on the rainfall. In river management the nature of rivers and deltas must be taken into account (Wang et al., 2007).

River patterns provide information about a river's physical characteristics and behavior (Nanson and Knighton, 1996), reveal something about the dynamics of a river system, and represent a mode of channel form adjustment in the horizontal plane, which is linked with transverse and lengthwise modes (Schumm, 1985; Knighton, 1998). Original classification of river patterns by Leopold and Wolman (1957) into straight, meandering and braided formed a basis for future research on fluvial forms and processes. Anastomosing river is recognized as a river pattern, which is different from braided (Schumm, 1968; Smith, 1976; Rust, 1978; Knighton and Nanson, 1993). Nanson and Knighton (1996) examined the range of conditions in which anabranching systems form, grouped the anabranching system into different types, and explained why some rivers form anabranches (Huang and Nason, 2007). In this paper, a special river pattern, very different from other patterns and closely related to the male rivers-parasitizing river form, is discussed.

2 Gender of delta

Male and female deltas have very different natures. Male deltas extend into the ocean, forming a fan-shape delta and an extrusive river mouth. Male deltas have only one or two channels. On the other hands, female deltas consist of complex channel networks and numerous islands or bars. In general, male deltas are dynamic and female deltas are stable. Female deltas provide multiple stable habitats and, therefore, have high biodiversity. Table 1 lists the main features of typical male and female rivers. The Yellow River delta is the most typical male delta and the Yangtze River delta is a female delta.

Table 1 Basic features of male and female deltas

River	Yellow[1]	Yangtze[2]	Missi-ssippi[3]	Ural[4]	Luanhe[5]	Irrawaddy[6]	Pearl[7]	Rhine-Meuse[8]	Volga[9]	Nile[10]	Ebro[11]
Length (km)	5,464	6,300	6,021	2,534	877	2,714	2,214	1,320	3,688	6,670	927
Watershed (10^3km^2)	752	1,800	3,220	231	45	410	454	224	1,380	2,870	86
Runoff (10^9m^3)	31.3 (1952-05)	903.4 (1950-05)	380.0	8.0	4.5	379.0	284.9	79.0	810.3	90.9	42.0
Annual load (10^6 t)	778 (1952-05)	414 (1951-05)	495	2.8	20.1	325	75.9	3.5	27	134	30
Load/water (kg/m^3)	24.856	0.458	1.303	0.350	4.514	0.858	0.266	0.044	0.033	1.474	0.714
D_{50} (mm)	0.019	0.009	0.010		0.065	0.0105		0.010		0.005	0.062
Delta area (km^2)	5,450	50,000	2,108	671	82	32,400	11,300	35,000	20,000	23,300	330
Tidal range (m)	1.30	2.67	1.20	0.01	1.4	2.71	1.35	2.00	0.01	0.43	0.10
Gender	Male	Female	Male	Male	Male	Male	Female	Female	Female	M-F	Male

Note: 1. MWRC, 2009; 2. Yang et al., 2003; MWRC, 2009; 3. LCWCRTF and UACE, 2000; Kesel, 2003; 4. Kosarev, 2005; Lagutov, 2008; Lahijani et al., 2008; 5. Feng and Zhang, 1998; 6. Robinson et al., 2007; Furuichi et al., 2009; 7. Mao et al., 2004; Huang et al., 2004; Dai et al., 2008; 8. Thonon and Perk, 2003; 9. Coleman and Roberts, 1987; Kosarev and Yablonskaya, 1994; Kroonenberg et al., 1997; Overeem et al., 2003; 10. Shalash, 1982; El Askary and Frihy, 1986; Stanley, 1988; Ahmed, 2008; 11. Palanques et al., 1990; Jiménez et al., 1997; Guillén and Palanques, 1997; Sánchez-Arcilla et al., 1998; Canicio and Ibánez, 1999; Rovira and Ibàñez, 2007.

2.1 Male deltas

The Yellow River is the second longest river in China. The river watershed is mostly arid and semi-arid with a long term-average annual runoff depth of only 77 mm and a total annual runoff of all tributaries of 58 billion m^3. The average annual sediment load in the period from 1950-1985 was 1.6 billion tons at Huayuankou (Zhengzhou), ranked first in the world, with the highest annual load of 3.9 billion tons. The figures at Lijin, the most downstream hydrological station on the delta, were smaller because water was diverted and sediment deposited in the lower reaches of the river. The river has unloaded a lot of sediment onto the channel bed in the lower reaches. Over time, a perched river formed that frequently breached its levees. From BC 602 to 1949 the river experienced 1,593 levee bursts, flooding vast areas and claiming millions of human lives. The river shifted its major course (600-700 km long) by avulsion 26 times with the apex around Zhengzhou resulting in devastating calamities and numerous old channels, including 8 major shifts with the river mouth alternating between the Bohai Sea and the Yellow Sea. Figure 1 shows the migration of the river from BC602 to 1855, the old channels, and the land created by the river.

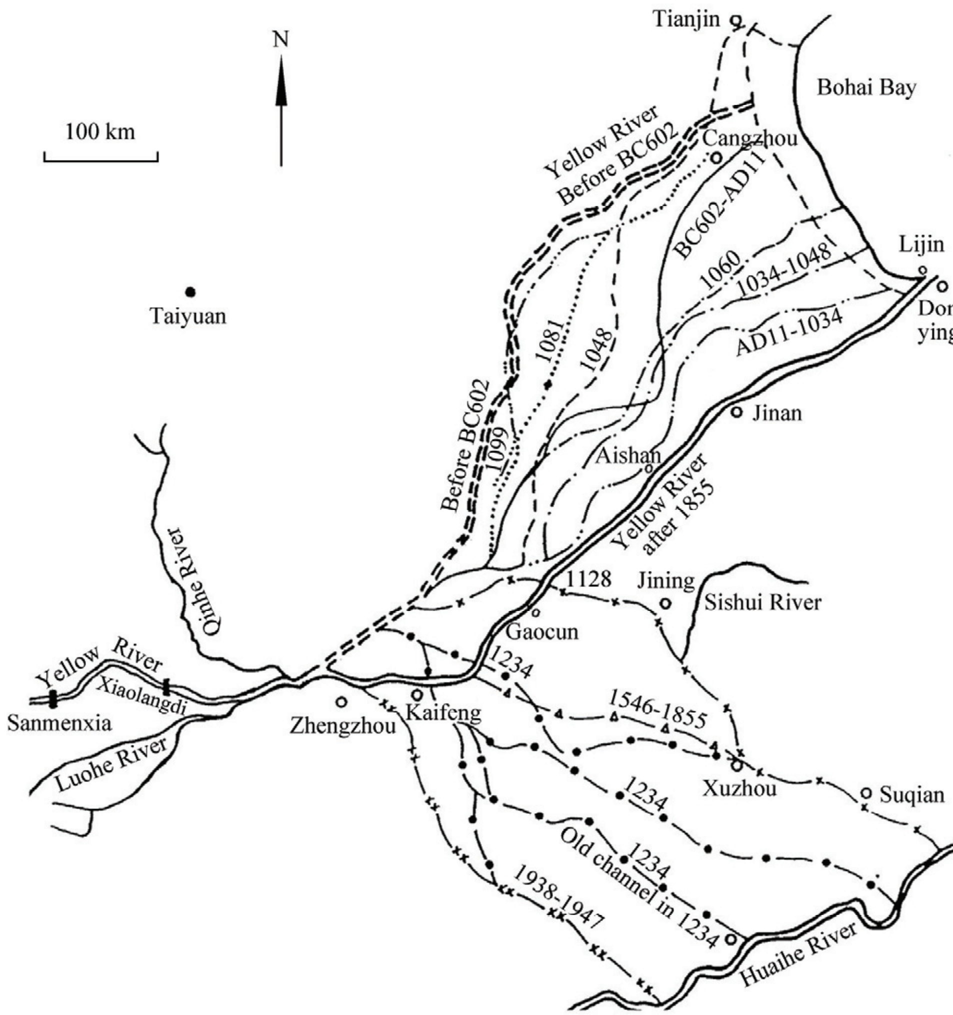


Fig. 1 Migration of the lower Yellow River and old channels due to avulsions in the past 2600 years

The present Yellow River has flowed into the Bohai Sea via Lijin since the river levee at Tongwaxiang (about 600 km from the present river mouth as shown in Fig. 1) was broken and floodwater captured the Daqing River channel, in 1855. Thence the reaches upstream of Lijin have been enhanced and reinforced many times, and no avulsions or channel shifts occurred in these reaches since 1855. The population density downstream from Lijin was low and the levees downstream of Ninghai were weak to resist the assault of flood. Nodal avulsions occurred around Ninghai, which is about 100 km from the present river mouth, as shown in Fig. 2. The river changed its delta channel 11 times between 1855 and 1976. Each channel had its own name, such as Diao-kou-he and Shen-xian-gou. The channels had an average life of only about 10 years. In general, the lengths of the new channels were about 1/3 -1/2 of the previous ones and the gradients were 2-3 times higher (Wang et al., 2003). The present delta was created by rapid sediment deposition in the past one and a half centuries, accompanied by frequent shifts of the channel in the area. The 12 old river channels are shown in Fig. 2 (Wang and Liang, 2000). The present channel-named Qing-shui-gou Channel- has been in use since 1976. In the 1980s, the avulsion was controlled because an oil field and petroleum industry had developed in the delta and a lot of infrastructures prohibited the river channel from shifting.

Figure 2 shows the Yellow River delta, which had extended into the Bohai sea for more than 40 km since the avulsion from the Diao-kou-he channel to the Qing-shui-gou channel in 1976 (Zhang et al., 1997). In 1996, the Qing-shui-gou Channel had been used for 20 years and a small artificial avulsion was performed from the old Qing-shui-gou channel (southeastern) to the Qing-shui-gou-Chahe channel (northeastern), which involved only a short distance of the river channel (16 km). Four years later the flow in the old Qing-shui-gou channel was cut off by sedimentation. No more sediment is transported to the old mouth and the old mouth began to retreat due to coastal erosion. The tidal range at the river mouth is about 0.8 m and the river channel gradient is about 0.012%. Thus, the tidal flow affects only a short distance of the river (about 10 km only).

In general, male rivers have only one or two delta channels, which is very different from female rivers. Moreover, many male rivers often create land at high rates, and thus, result in the quick expansion of the deltas. Figure 2 shows the land created by the Yellow River during the period from 1855-1976 and from 1976-1996. During the Qing-shui-gou Channel period from 1976-1996, the river created land at a rate of 20-40 km^2/year. It followed the process of "channel siltation - high flood - broken levee - channel shift - creation of new land." In the early Qing-shui-gou period, the river channel was not well shaped. The sediment-laden flow built up its channel by depositing sediment in low velocity areas and scouring sediment in high velocity areas. During this process, seasonal variation of discharge and sediment deposition in the delta area has resulted in a high frequency of mouth migration. In the first 3 years (1976-1979), the channel was unstable and the new river mouth wandered in a range of 30 km. The main stream flowed eastward into the sea in October 1977, but changed northward in October 1978. In the flood season of 1979 the river mouth moved from northeast to southeast again. The frequent shifts of the mouth and channel were due to the floods during these years with sediment high concentration with a maximum sediment concentration up to 240 kg/m^3. Since 1980, the main channel has moved east again and a relatively stable mouth formed. The average speed of the river mouth moving into the sea was about 2.3 km/yr in the period from 1976-1994 and was zero in the period from 1994-1996. The rate of land creation was greatly reduced or stopped because of sediment load reduction from about 1 billion tons per year in the 1970s to less than 0.1 billion tons per year in the 2000s.

There is an oil field in the Yellow River delta. The river was artificially switched to the Chahe Channel in July 1996 for oil land creation (Zhang et al., 1997). When the first flood flowed through the Chahe Channel in 1996, erosion took place and the channel became deep and wide. The new channel can be clearly seen from the satellite image shown in Fig. 3. Because the new channel was 16 km shorter than the previous one, the energy slope was higher and retrogressive erosion occurred in a section of 30 km from the river mouth. The shift to the new channel reduced the flood stage upstream to Lijin by more than 0.3 m. More than 60 km^2 of land was created at the new river mouth by the 1996 flood. A new oil field has emerged on the newly created land. This was a successful operation integrating river mouth training and oil production.

The Mississippi River in the U.S., the Luanhe River in China, the Ebro River in Spain and the Ural River in Russia are also male rivers. The basic features of these rivers are given in Table 1. Figure 4 shows the Ural and Ebro deltas. Both exhibit features similar to the Yellow River delta. The Ebro River is 928 km long and has a watershed area of 85,835 km^2. The Ebro watershed was a closed basin until its opening to the Mediterranean Sea 5.3 million years ago. In the following 1.6 million years the river extended into the sea and formed the ancient Ebro delta about 3.5 Million years BP, which was larger than the present Ebro Delta (1). Canicio and Ibánez (1999) used ancient maps and reconstructed the revolutionary sequences of the delta in the past millennium. The river mouth was located to the southwest of the present mouth and the river flowed southeastward into the sea about 800 years ago. The river shifted its delta course and flowed northeastward into the sea before 1580. There are two delta lobs shown in the 1580 map because the new delta lob had been formed and the old one still existed. In 1750 the river shifted its channel to the present channel. In the following 100 years, the river extended into the sea for about 5 km and reached the present location of the mouth. Figure 4 (right) shows the southern deltaic lobe and the northern deltaic lobe in the past and the present lobe and the river mouth (Maldonado, 1972). The present river mouth is receding due to sharp sediment load reduction in the past decades, which is discussed in the section 3.1.

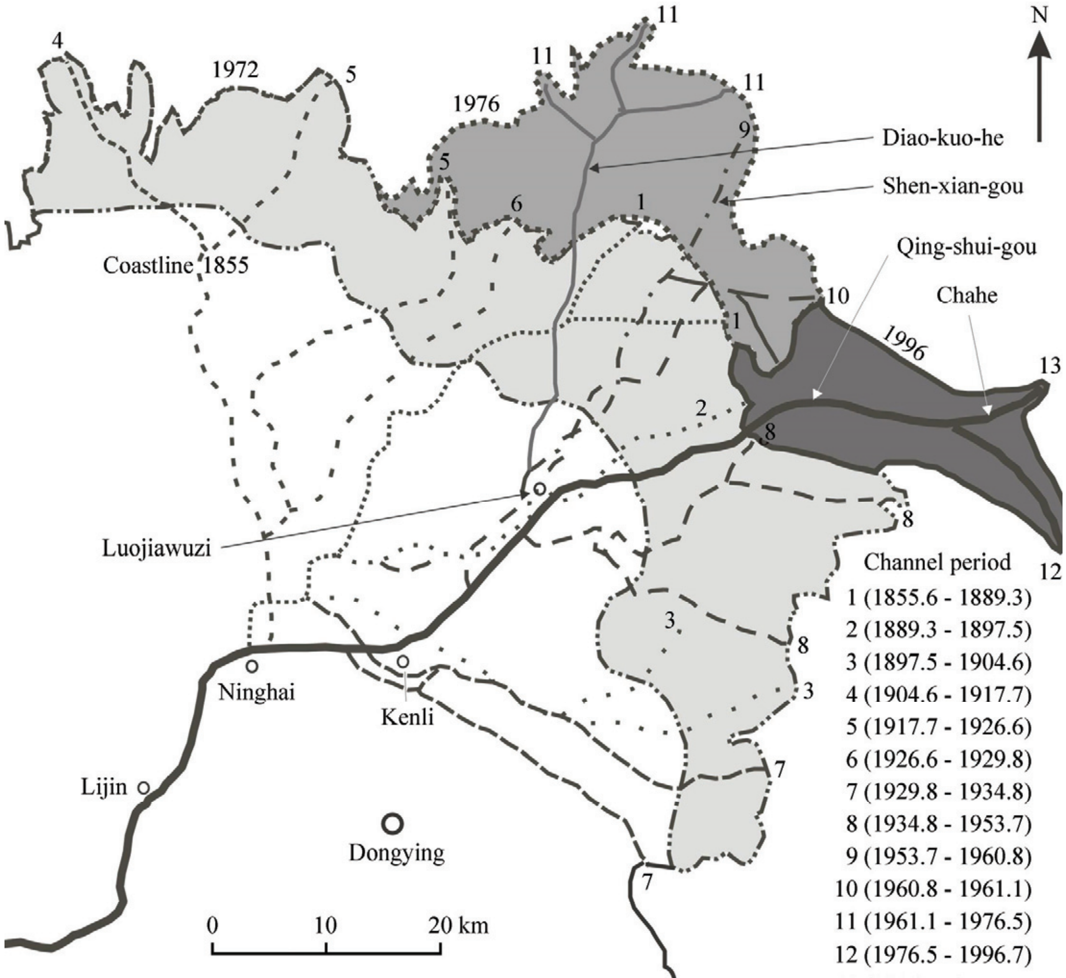


Fig. 2 Nodal avulsions and the abandoned channels on the present Yellow River delta

Fig. 3 Satellite image of the Yellow River mouth and shift of delta channel to Qing-shui-gou-Chahe channel in 1996

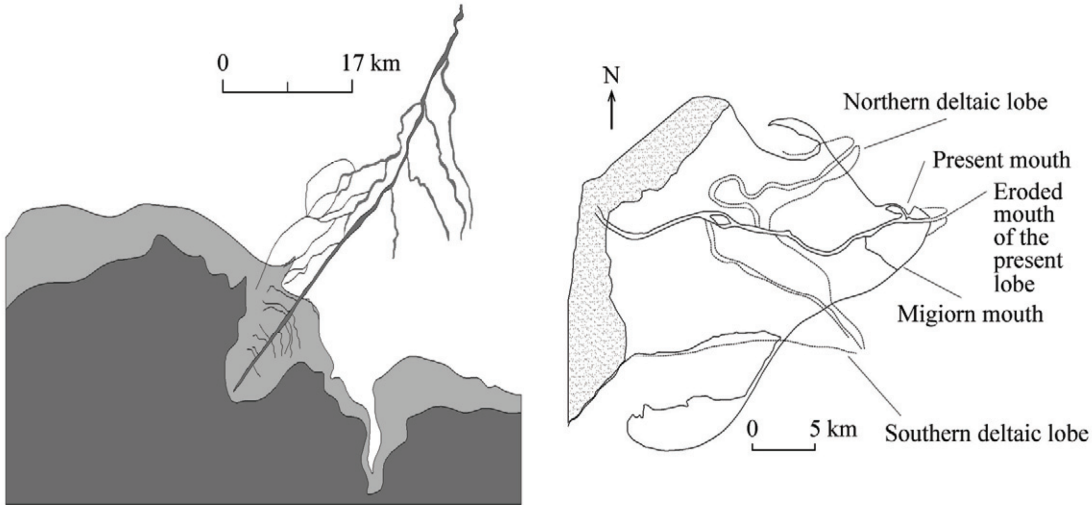


Fig. 4 Ural delta (left) and Ebro delta (right) extend into the sea, which show male delta features (after Maldonado, 1972)

2.2 Female deltas

The Yangtze River delta is a typical female delta, as shown in Fig. 5. The river mouth of the Yangtze is located in Shanghai. The river mouth has undergone significant geomorphologic changes over the past 3,000 years (Chen et al., 1988). The Chongming Island appeared in the river mouth some 800 years ago and divided the river into the North Branch and South Branch. Prior to the 18th century the North Branch was the main discharge channel; since then the main flow has shifted gradually to the South Branch. The North Branch discharge has decreased. The North Branch accounted for 25% of the river runoff in the 18th century and now only discharges river runoff during low tides in the flood season. The discharge ratio decreased to about 2% in the 1950s and is now about -8% since more tidal water flows upstream. Furthermore, the South Branch was bifurcated into the North Channel and the South Channel by Changxing and Hengsha islands, which emerged from the South Branch after the 100-year flood in 1860 (Le, 1998; Yang et al., 2005, 2007; Wang et al., 2007). A sand bar, namely Jiuduan Shoal, appeared after a major flood 1954 and is now growing in the South Channel, and further divides the South Channel into the North Passage and South Passage.

The thalweg of the ebb tidal current and river flow is directed to the right bank due to the action of the Coriolis force, forming the ebb tide channel, while the thalweg of the flood tidal current is directed to the left forming the flood tide channel. The flood tide direction is about 305° from the sea toward the river while the ebb tide current direction is 90°-115°. There is a 10°-35° angle between the extension line of the flood and ebb tidal currents because of the Coriolis force. Ebb tidal current is diverted to the south, while the flood tidal current is diverted to the north. Thus, between the flood and ebb tidal currents in the river mouth area there is a slack water region where sediment rapidly deposits to form shoals that eventually coalesce to form estuarine islands. Consequently, the river flow is bifurcated. Over time numerous islands have developed in the estuary and a complex channel network has formed.

Figure 6 shows the development process of the Jiuduansha Shoal (Xie et al., 2009). The longitudinal section of the Jiuduansha Shoal forms a convex geomorphic pattern, which stands out on the link between the -10 m isobathic from the upper reach section to the lower reach section of the Yangtze River estuary (Fig. 5 A-A´). In transverse section, the Jiuduansha Shoal is confined between the channels of the South Passage and the North Passage (Fig. 5 B-B´). The area around the Jiuduansha Shoal is the major place for the sediment deposition in the South Branch and South Channel. The sediment deposits during the flood season and erodes during the low flow season, with the sediment depositing at neap tides and eroding during spring tides under the action of runoff and the tidal current.

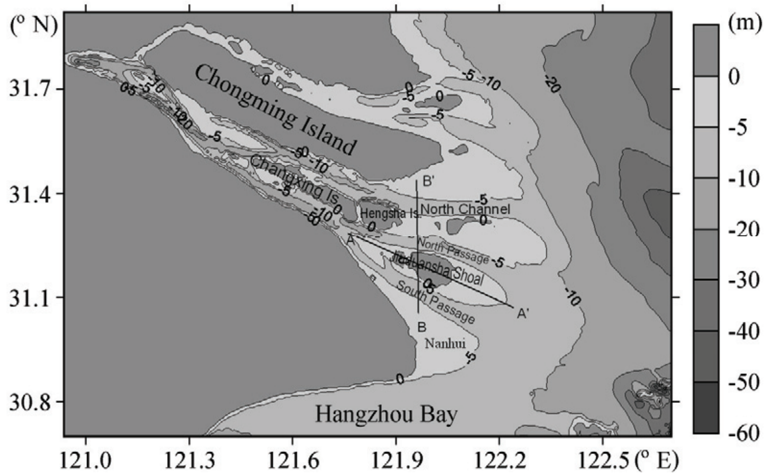


Fig. 5 The Yangtze River delta - Chongming Island divides the river into the North and South Branches; Changxing Island divides the South Branch into the North and South Channels; and Jiuduan Shoal divides the South Channel into the North and South Passages

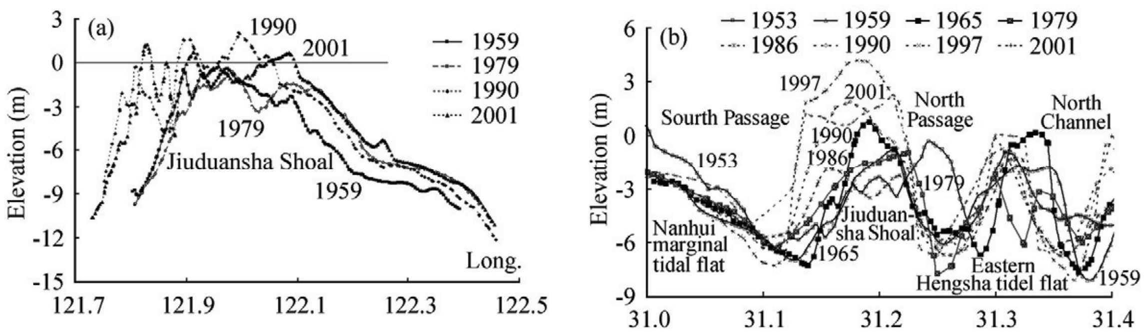
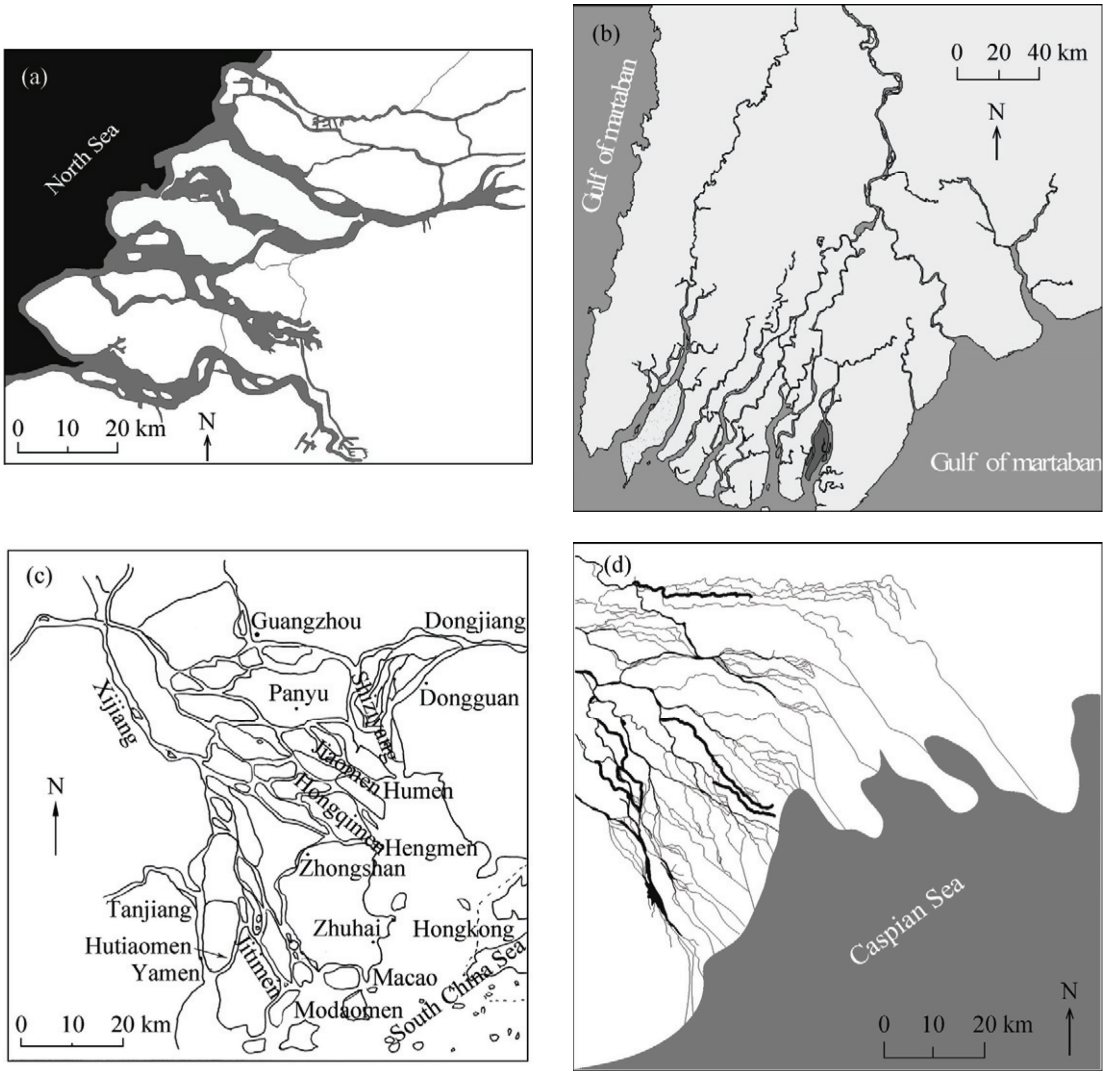


Fig. 6 Development of the Jiuduansha Shoal: (a) Longitudinal section of the Jiuduansha Shoal (121°35′E, 31°16′N - 122°25′E, 31°5′N, Figure 5 as A-A') from 1959 to 2001; (b) Cross section of the Jiuduansha Shoal at 122°E (Figure 5 as B-B') from 1953 to 2001

Figure 7 shows several female deltas: (a) Rhein-Meuse-Scheldt delta; (b) Irrawaddy delta; (c) Pearl delta; and (d) Volga delta. The Rhein-Meuse-Scheldt Delta and the Pearl River delta are female as well. The Rhein-Meuse-Scheldt delta consists of a very complex channel network, as shown in Fig. 7(a). The Rhine River begins at the Rheinwaldhorn Glacier in the Swiss Alps and flows north and east approximately 1,320 km. At the Netherlands frontier, it divides into two parallel distributaries, the Lek and the Waal, as it crosses a wide, marshy plain and a great delta before entering the North Sea. The river Meuse links with the Rhine at the delta and forms a complex channel network. The Scheldt River also joins the channel network at the delta. There are many channels in the delta and many islands between the channels.

The Pearl River has a drainage area of 450,000 km^2, carrying 3.086 trillion m^3 of water and 87 million tons of sediment load annually into the South China Sea. The sediment load/water ratio is only about 0.03 kg/m^3, thus a female delta has developed in this location. The delta has a complex channel network that consists of the West River, North River, East River, and Tanjiang, Suijiang, Liuxi, and Zengjiang Rivers. Sediment from these rivers has deposited at the bay and has formed many islands. Channels connect with each other like a spider web. The river water flows into the South China Sea through eight large mouths: Humen, Jiaomen, Hengmen, and Hongqili from the east, and Modaomen, Jitimen, Hutiaomen and Yamen from the west, as shown in Fig. 7(c) (after Wang et al., 2005).



(a) Rhine-Meuse-Scheldt delta; (b) Irrawady delta; (c) Pearl River delta; and (d) Volga delta

Fig. 7 Female deltas consist of numerous islands and spider-web like channels

3 Change of river gender

3.1 Gender change

In general, male deltas develop if the sediment load/water ratio is high and the tidal current is weak, e.g. the Yellow River delta. If the load/water ratio is not high and tidal current is strong a female delta develops, e.g. the Yangtze River delta. Figure 8 shows the gender of the delta (thus gender of the river) as a function of sediment load/water ratio and tidal range. Points of female deltas are in the upper-left zone and points of male deltas are in the bottom-right zone. There is a transitional zone between the male and female areas. The impoundment of a river can cause the river to change genders because dam construction traps a lot of sediment, resulting in a reduction of the load/water ratio by 70-99%. The Nile River and the Ebro River are changing from male to female due to remarkably reduction in the sediment load transported to the deltas.

The Mississippi River mouth extends deeply into the Mexico Gulf. Avulsions occurred in the Mississippi delta along the coast of Louisana as successive channels searched for higher gradient than their precursors (Leeder, 1983). Delta development is affected or partly controlled by humans. Upstream reservoirs, changes in agricultural practices and land uses, and bank stabilization measures have reduced average sediment loads in the lower Mississippi River by approximately 67% since the 1950s (Kesel, 1988). The average concentration of suspended sediment reduced from 0.8 kg/m^3 in 1950 to 0.24 kg/m^3 in 2000. Moreover, the natural avulsion from the present Mississippi River channel to the Atchefalaya channel has been stopped by human structures. The present delta is eroded by waves and tidal current. The delta lobe has become slender and thin.

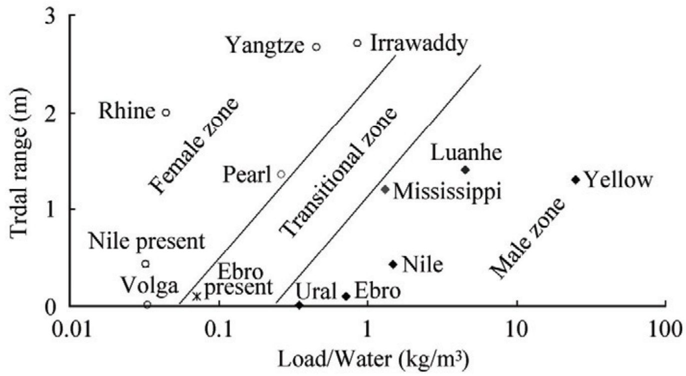


Fig. 8 Gender of the delta as a function of sediment load/water ratio and tidal range

The Nile River flows 6,825 km from central Africa to the delta and is the longest river in the world, which is the reason for the existence of Egypt and the great Egyptian civilization. It is an exotic river with no perennial-flow tributaries, but ephemeral wadis contribute sediment and water infrequently. In contrast to other large rivers, the Nile is straight, and appears to be relatively stable. The Nile today has been described as a "very low energy river with little capability to erode its banks (only 12% of its banks are experiencing erosion) or change its channel" (Mercer et al., 1992). In the past centuries the Nile River was a male river with annual sediment load about 160 million tons. The sediment concentration was as high as about 3.5 kg/m^3. A fan-shape delta developed with two channels extending into the red sea (Stanley and Warne, 1994). The delta, with an area of about 23,300 km², has been formed through deposits over the course of tens of thousands of years on the originally shallow seabed. The area around the Nile has about 34 million inhabitants, which equates to half the entire population of Egypt. The coastline is about 400 km long, from Alexandria in the west to Port Said and the outlet of Suez Canal in the east. The construction of the Aswan Dam and the High Aswan Dam in addition to many barrages has changed the river remarkably. The river's long-term annual peak discharge of 8,430 m^3/s has been reduced to a maximum release of 2,550 m^3/s, while the suspended sediment concentration in flood season is now only about 0.1 kg/m^3 (Stanley and Winkley, 1994). These changes affect the delta development and coastal erosion of the delta. At the present, there are several brackish lagoons or lakes, of which Manzala and Burullus are the largest. The delta has two main channels: the Rosetta and Domietta rivers. The sediment load has been reduced by 99% due to dams and barrages. Thus, the delta has changed from male to female. A stable channel web consisting of numerous distributaries and canals has been formed, as shown in Fig. 9(a).

The sediment load reduction also caused the Nile delta to change from a sediment deposition center into a man-altered coastal plain. The delta has stopped spreading out into the Mediterranean and locally is receding. It is no longer an active natural delta. Very little sediment is presently carried seaward to replenish the delta coast. The Nile has transformed from a seasonally fluctuating fluvial regime to a year-round storage and regulated flow system (Howell and Allan, 1994). As shown in Fig. 9(b) the tip of the delta channel is retreating and the delta lobe has eroded (after Torab and Azab, 2007). The extended length of the river mouth has been shortened by 8 km in the past 80 years. The land loss was caused not only by wave current and dams and barrages, but also by retention of sediment on the delta plain due to channelization, irrigation and land reclamation on the delta proper (Stanley, 1988, 1996).

The Ebro delta is located on the Spanish Mediterranean coast about 200 km southwest of Barcelona. The delta's outer coastline has an approximate length of about 45 km. After several centuries of growth, the delta is changing from male to female because the sediment load has been reduced by 99%. The delta is currently in the transmit zone between the male and female zones. Numerous dams have been constructed in the lower Ebro river course (Palanques et al., 1990). This decrease in sediment discharge has been especially dramatic for sandy sediments, which are the ones that are directly incorporated in the littoral dynamics. Present sand supplies by the Ebro River have been estimated at about 30,000 m^3/year, which is only 1% of the long-term average value (Guillén and Palanques, 1992; 1997). As a result of this drastic decrease in the river sand discharge an intense reshaping of the deltaic coast has begun to take place, resulting in strong erosion along specific coastal stretches (Jimknez et al., 1997). Figure 10 shows that the river mouth has retreated several kilometers due to the sediment load reduction (Ibánez and Rovira, 2009). In the meantime, more channels appeared on the delta. Although the new channels are a result of human activities, persistence of these channels implies the delta has been losing its male delta features. It may be predicted that more channels will appear and the delta will eventually change into a female delta in several decades.

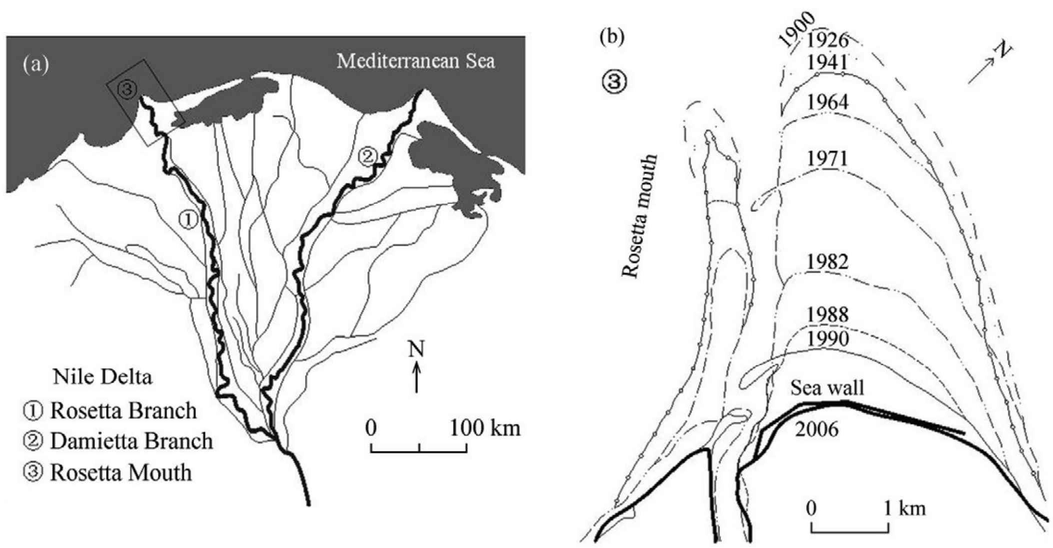


Fig. 9 (a) A channel web has developed on the Nile Delta in the process of gender change; (b) the river mouth of Rosetta channel has retreated by 8 km in the past 80 years due to sediment load reduction (after Torab and Azab, 2007)

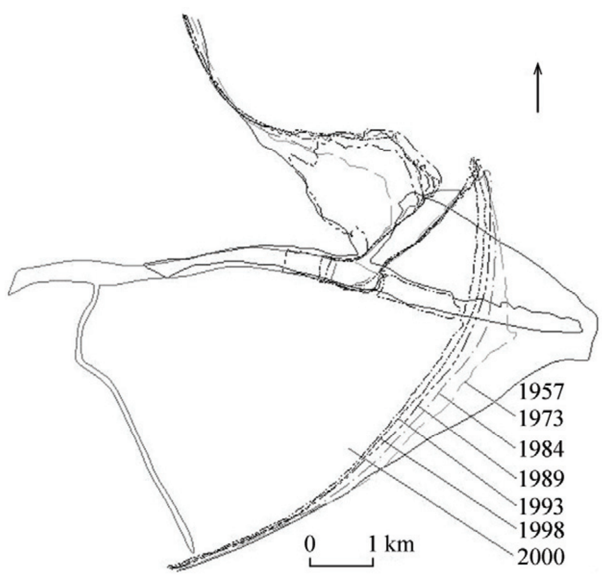


Fig. 10 Retreating Ebro delta due to sharp reduction in sediment load in the past 50 years (after Ibánez and Rovira, 2009)

3.2 Effects of gender change on ecology

In general, a river changes its gender from male to female due to sediment load reduction. Sharp sediment load reduction reduces land creation and causes problems to estuary management. For instance, sediment load reduction in the Yellow River has stopped land creation and resulted in land loss due to coastal erosion. In the Mississippi delta sediment load reduction has resulted in wetland loss. Nevertheless, if a gender change does not occur too fast and the delta has no severe pollution, the ecology may improve and the biodiversity of both fish and macro-invertebrates will increase after the gender change.

Female rivers provide stable habitats for both terrestrial and aquatic bio-communities and therefore have a higher biodiversity than that of male rivers. Benthic invertebrates and fish are main elements of aquatic ecology. Streambed sediment is one of the main factors affecting the biodiversity of benthic invertebrates (Duan et al., 2009). Samples of fish were taken from the lower reaches and samples of macro-invertebrates were taken from the beds of the lower reaches of the Yellow, Yangtze and Pearl rivers (Yi et al., 2008). Benthic macro-invertebrates were taken with a kick-net with holes of 420 μm and a weighted Petersen grab (1/16 m^2) and then sieved with a 420-μm sieve. Several sites were chosen for sampling for each river. Specimens were manually sorted out from sediment on a white porcelain plate and preserved in 75% ethanol. All species were identified under microscopes by experienced biologists. Fish samples were taken from the lower reaches of the Yangtze and Pearl rivers by hiring fishermen and using seine. For each river, four fishermen captured fish species for 3 days.

Table 2 lists the species of invertebrates and fish sampled from the lower reaches of the Yellow, Yangtze and Pearl rivers. The Yellow River is a male river and its channels are unstable. Erosion and sedimentation occurred occasionally. Samples of macro-invertebrates were taken from 6 sites selected from the lower reaches of the Yellow River. Only one species *Palaemonidae* (shrimp) was found from the river channels. Another eight species of invertebrates were sampled from a riparian wetland in the Yellow River delta. The extremely low biodiversity was caused by erosion, sedimentation of the river bed, and migration of the channel. There are only a few fish species in the lower Yellow River and the abundance level of fish is low. Therefore, the Yellow River has no fisheries and no fisherman can be hired for fish sampling.

Female rivers have stable habitats and low sediment load, therefore, they have high biodiversity. The taxa richness and abundance of invertebrates and fish were much higher in the Yangtze and Pearl rivers than in the Yellow River. The results support the conclusion that habitat stability is the most important factor for high biodiversity (Wang and Xu, 2010). Fish samples were taken from six sites in the lower reaches of the Yangtze River, 43 species belonging to 11 families of fish were found from the 6 sampling sites. In the Pearl River, 70 species belonging to 29 families of macro-invertebrates were found from 18 sampling sites and 68 species belonging to 25 families of fish were found from 9 sampling sites.

The biodiversity in the female rivers are much higher than that of male rivers. In general, if a river changes its gender from male to female the biodiversity increases. Nevertheless, the causes of gender change (dam construction and water and sediment diversion) and the gender change itself are stresses on the bio-communities. Therefore, the ecology may be impaired during the gender change.

4 Parasitizing rivers attached to male rivers

Male rivers carry heavy sediment load to the lower reaches and deltas. Humans made continuous effort to control floods by constructing and enhancing grand levees. Overtime, the male rivers become perched rivers in their lower reaches and deltas. Over the course of time avulsions occurred and thus created many abandoned channels. Some abandoned channels have combined with other rivers and formed new river systems. Some abandoned channels have been cut into several depressions or wetlands, or totally disappeared due to human reclamation. Other abandoned channels still exist and rely on their father river. Moreover, male rivers have no tributaries in the perched reaches; instead, rainwater falling on the surrounding land of the river flows in new drainage channels parallel to the levees. These abandoned channels and new drainage channels are not tributary or distributary rivers, but their location and stability depend on their father rivers. These channels are parasitizing rivers of the male river.

Table 2 Species of invertebrates and fish in the lower reaches of male and female rivers

River (Gender)	Species of macro-invertebrates and fish
Yellow (Male) Sampling sites: 6 for invertebrates	Invertebrate (9 species, 7 families): *Palaemonidae, Branchiura, Limnodrilus, Tipulidae, Planorbidae, Stenothyra, Lymnaeidae, Bithynia, Chironomidae* sp. Fish (no samples): few species and very low abundance
Yangtze (Female) Sampling sites: 4 for fish; 0 for invertebrate	Fish (43 species, 11 families): *Mylopharyngodon piceus, Ctenopharyngodon idellus, Hypophthalmichthys molitrix, Cypriniformes carpio Linnaeus, Cypriniformes auratus auratus, Parabramis pekinensis, Silurus asotus Linnaeus, Pelteobagrus fulvidraco, Coreius heterodon, Distoechodon tumirostris, Misgurnus anguillicaudatus, Hemiculter leucisculus, Coilia ectenes, Coilia brachygnathus, Leptobotia Bleeker, Leiocassis longirostris Günther, Rhinogobio Bleeker, Saurogobio dabryi Bleeker, Channa argus, Odontobutis obscurus,Simiperca scherzeri steindachner, Lateolabrax japonicus, Erythroculter dabryi, Culter erythropterus Basilewsky, Pseudorasbora parve, Sarcocheilichthys nigripinnis, Hemiramphus kurumeus, Mystus macropterus*
Pearl (Female) Sampling sites: 18 for invertebratres 9 for fish	Invertebrates (70 species, 29 families): Nematoda, Nereididae, Nereididae, Spionidae, *Pseudopolydora paucibranchiata* (Okuda), Capitellidae, Naididae, *Dero digitata* (Müller), *Branchiodrilus semperi* (Bourne), *Slavina appendiculata* (d'Udekem), *Limnodrilus grandisetosus*, Nomura, *Limnodrilus claparedeianus* Ratzel, *Limnodrilus* sp., *Aulodrilus limnobius* Bretscher, *Aulodrilus pigueti* Kowalewski, *Aulodrilus pluriseta* (Piguet), *Branchiura sowerbyi* Beddard, *Glossiphonia* sp., *Helobdella* sp., *Erpobdella* sp., Bithyniidae, *Alocinma longicornis* (Benson), *Bithynia misella* (Greller), *Stenothyra glabra* A. Adams, *Bellamya purificata* (Heude), *Bellamya* sp., *Margarya* sp., *Rivularia globosa* Heude, *Pila* sp., *Semisulcospira cancellata* (Benson), *Semisulcospira libertina* (Gould), *Semisulcospira* sp., *Melaniodes tuberculata* (Müller), *Radix auricularia* (Linnaeus), *Radix lagotis* (Schrank), *Radix swinhoei* (H. Adams), *Galba* sp., *Hippeutis cantori* (Benson), *Hippeutis umbilicalis*, Mytilidae, *Limnoperna lacustris* (Martens), Unionidae, *Anodonta woodiana woodiana* (Lea), *Corbicula fluminea* (Müller), Amphipoda, Acarina , *Baetis* sp., *Ephemerella* sp., *Lamelligomphus* sp., *Megalogomphus* sp., *Leptogomphus* sp., *Parachauliodes* sp., *Neochauliodes* sp., Ceratopogonidae, Tipulidae, Dolichopodidae, Muscidae, *Clinotanypus* sp., *Nanocladius* sp., *Procladius* sp., *Tanypus* sp., *Cricotopus* sp., *Eukiefferiella* sp., *Parakiefferiella* sp., *Chironomus* sp., *Cladotanytarsus* sp., *Cryptochironomus* sp., *Cryptotendipes* sp., *Demicryptochironomus* sp., *Dicrotendipes* sp., *Endochironomus* sp., *Microchironomus* sp., *Polypedilum* sp., *Rheotanytarsus* sp., *Stictochironomus* sp., *Tanytarsus* sp. Fish (68 species, 25 families): *Squaliobarbus curriculus, Channa maculate, Takifugu ocellatus, Erythroculter recurviceps,Pelteobagrus vachelli,Cranoglanididae bouderius bouderius, Pelteobagrus fulvidraco, Pseudogobio vaillanti vaillant, Clupanodon thrissa, Coilia grayi, Megalobrama terminalis, Cirrhina moitorella, Mugil cephalus Linnaeus, Xenocypris davidi, Sparus latus* Houttuyn, *Tilapia mossambica, Nemacheilus fasciolatus, Botia robusta, Acrossoch eilus parallens, Leiocassis virgatus, Squalidus argentatus, Garra orientalis, Culter erythropterus Basilewsky, Osteochilus salsburyi* Nichols et Pope, *Hemibarbus labe,Clarias fuscus, Ptychidio jordani, Saurogobio dabryi, Abbottina rivularis, Coilia grayi, Ptychidio jordani, Mystus guttatus, Varicorhinus gerlachi, Siniperca scherzeri, Parabotia maculosa, Plagiognathops microlepis, Saurogobio dabryi, Neosalanx taihuensis* Chen, *Siniperca kneri*
Notes	Fish samples were taken by hiring 4 fishermen and using seine for capturing different fish species for 3 days for the Yangtze and Pearl rivers. There is no fishery in the Yellow River and no fishermen to be hired for sampling.

The lower Yellow River is a perched river with its riverbed more than 10 m higher than the surrounding ground. The rain water can not flow into the river and water diversion from the river affects the fluvial process (Wang et al., 2008). Many drainage channels have developed on the levees and flow parallel with the Yellow River into the sea. Some of these rivers are rather long, with a length of 600-800 km. These rivers were created by the Yellow River and originate from the grand levees of the Yellow River. Their persistence and stability depends on the stability of the Yellow River. Figure 11 shows the Yellow River and its parasitizing rivers. Although the drainage areas of the parasitizing rivers are not in the Yellow River basin, they are controlled by the Yellow River. Therefore, the drainage areas are called parasitizing drainage areas of the Yellow River. The boundary of the parasitizing drainage area and the divide of the watershed of the Yellow River meet at Zhengzhou, which forms an X-shape structure, as shown in Fig. 11.

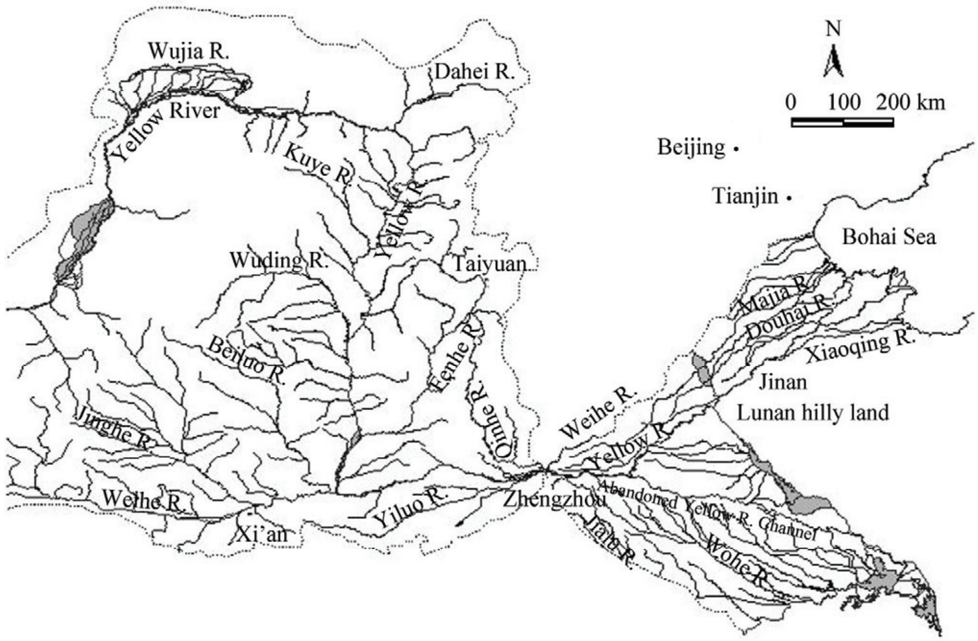


Fig. 11 The Yellow River and its parasitizing rivers

Small male rivers have their parasitizing rivers in their delta, which mostly developed from abandoned distributaries. Figure 12 shows the Luanhe River delta and its parasitizing rivers. The Luanhe River rises on the Mongolia Plateau, it travels through the Yanshan Mountains, and finally flows into the Bohai Bay. The average annual runoff of the river is 4.56 billion m^3, but 70–80% of it occurs in the flood season from June to September, and the flood season also transports 93% of the sediment load of 20.1 million tons. In 1915, the Luanhe River changed course to its present position, and has since developed its modern delta (Feng and Zhang, 1998). The delta land is 1–2 m above sea level. The sediment consists of mainly silt, fine sand and a small amount of clay. There are eight distributary courses. There is only one main drainage course for every period of development, the others tend to be abandoned gradually (Feng and Zhang, 1998). A few of them have developed into parasitizing rivers.

The parasitizing rivers on the Luanhe Delta become 300–500 m wide during a flood. The deposits in these channel beds are fine sand and sand. The upper reach is mainly composed of sand, but in the lower reach, there are many water pools, in which clays and silts are deposited. The dam construction and water and sediment diversion have caused the sediment load of the Luanhe River to decrease sharply to less than 1 million tons since 1980. The delta channel of the Luanhe River has become deep. As a consequence, the gender of river will change from male to female. The parasitizing rivers may finally link with their father-mother river and combine into a channel web like other female rivers.

Parasitizing rivers have no tributaries or mountainous watersheds. All runoff water comes from rain. Therefore, flow occurs only during rain season and the hydrograph of flow has only peaks and there is no flow between the peaks. Figure 13 shows the discharge hydrographs of the Majia River and Shahe River. The Majia River is a parasitizing river of the Yellow River, which is 425 km long and has a drainage area of 8,830 km^2. The river originates from the Beijindi Levee of the Yellow River. The river was once a channel dug by humans to drain the rainwater. Runoff is closely related to rainfall. In the past 20 years, discharge has increased faster than that of the period from 1956-1979 because urbanization and highway construction have reduced the infiltration capacity of the ground surface (Zhang and Jiang, 2004). To store water during rain season humans constructed many locks. Nevertheless, the storage capacity of these locks is limited and these locks have to be open after rainstorms.

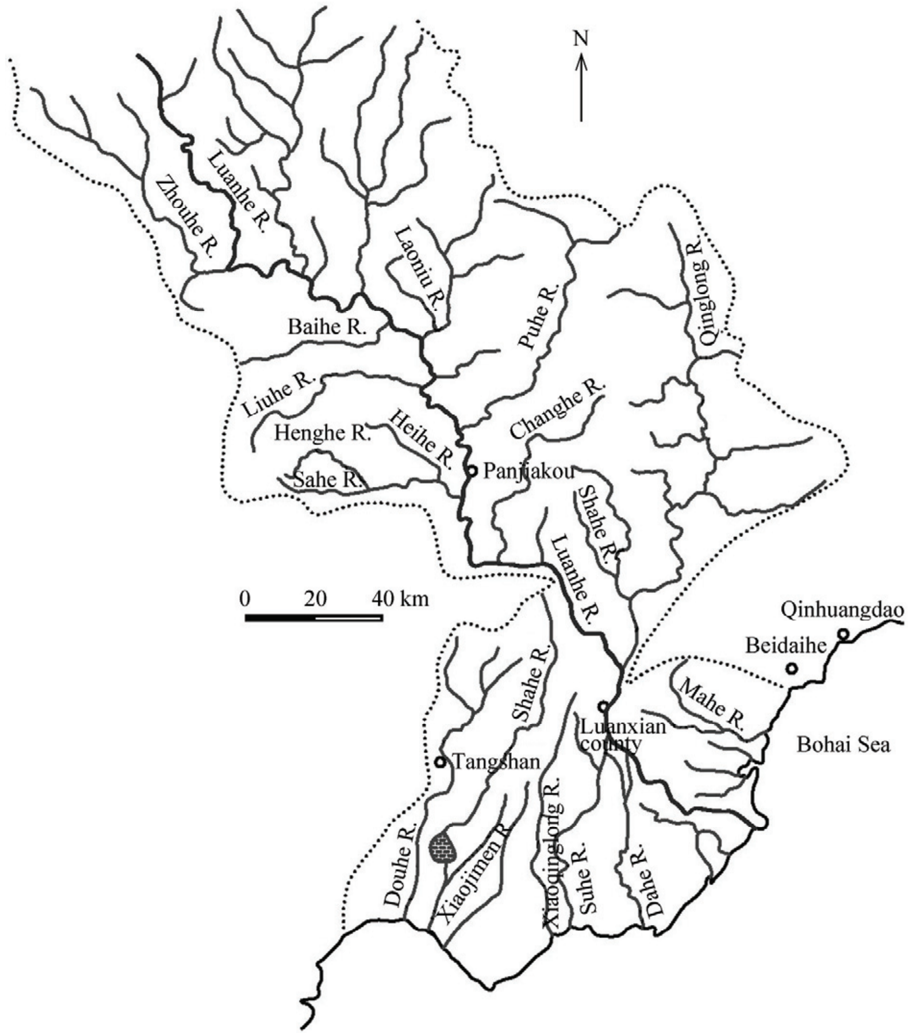
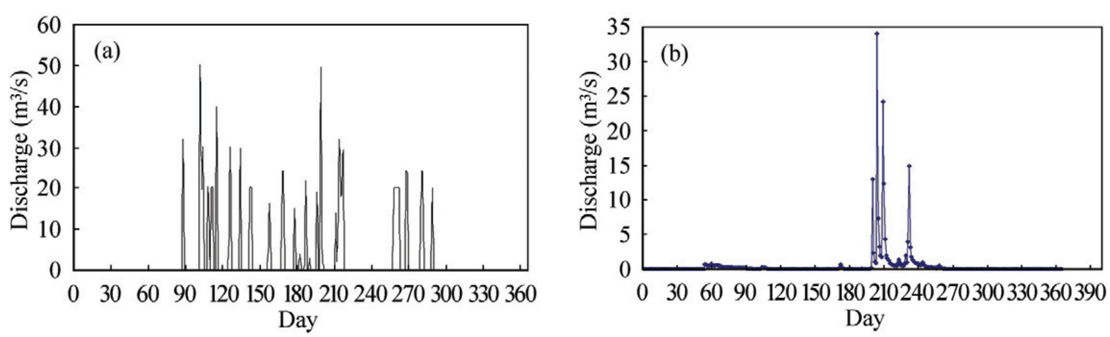


Fig. 12 The Luanhe River and its parasitizing rivers



(a) Discharge hydrograph of Majia River at Liuqiao Station in 2008

(b) Discharge hydrograph of Shahe River in 1963

Fig. 13 Sharp peaks of discharge during the rain season of parasitizing rivers:
(a) Majia River-a parasitizing river of the Yellow River;
(b) Shahe River- a parasitizing river of the Luanhe River

The Shahe River is 80 km long, which is a parasitizing river of the Luanhe River. The Shahe River was an abandoned channel of the Luanhe River after an avulsion of the delta channel. Flow occurs in the river only in July and August when rainstorms happen. Because the flood stage rises and falls very sharply and there is no water flow in the river during dry season the ecology in the river is poor. Weir and lock construction is the strategy to store water and improve the ecology.

5 Conclusions

Deltas can be classified into male deltas and female deltas. The Yellow, Mississippi, Luanhe, Ural and Ebro deltas are male deltas. The Yangtze, Rhein-Meuse-Scheldt, Pearl, Volga and Irrawaddy are female deltas. Male deltas extend into the ocean with only one or two channels, forming a fan-shape and a male genitals-like river mouth. Their development process is accompanied with periodic nodal or random avulsions. Male deltas develop if the sediment load/water ratio is high and the tidal range is weak. Female deltas consist of complex channel networks and numerous islands, bars and islands. Female deltas develop if the load/water ratio is low and tidal current is relatively strong. Female deltas provide stable and multiple habitats for various bio-communities. Therefore, the biodiversity of female deltas and the taxa richness of benthic invertebrates and fish are higher than that of male deltas. The gender of rivers may change from male to female due mainly to sediment load reduction.

In the lower reaches and deltas of male rivers the riverbeds are higher than the surrounding ground, and therefore, no tributaries flow into these rivers. Rivers originating from the levees and flowing parallel with the river into the sea developed naturally from the abandoned channels of the male river or by human activities. The appearance, persistence, length and stability of these rivers depend on the male river to which they are attached. These rivers are parasitizing rivers. Parasitizing rivers have no tributaries and little drainage area. The flow discharge exhibits very sharp peaks during rainfall. Management of parasitizing rivers must be integrated into management strategies of their father rivers.

Acknowledgements

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