RIVER CHANNEL CHANGE IN THE MIDDLE YANGTZE RIVER IN THE LAST 50 YEARS

– A CASE STUDY IN THE JIANLI SUB-REACH

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NATIONAL UNIVERSITY OF SINGAPORE

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Summary

Study on recent channel changes in the lower Jingjiang reach is of great importance in understanding intensive floods in the middle Yangtze River and assessing the impact of human activities on river channel evolution. With the application of GIS technique, this study has reconstructed historical river channel in the Jianli sub-reach at the end of the lower Jingjiang reach on the basis of hydrological survey data (pre-1987) and map materials (mainly navigation charts in 1981 and 1997).

Cross-sections derived from the hydrologic survey data suggest that the lower Jiangjiang reach has undergone undercutting in the riverbed. Analysis based on the map materials indicates that the channel, under the constraint of levees along the riverbanks, experienced a minor widening. Bank failure was also abundant due to the susceptible bank structure and increase of water discharge. Bank failure accelerated growth of sand bars in the channel. Two DEMs have been constructed from navigation charts (1:25,000) in 1981 and 1997. Cross-sectional changes derived from the DEMs present a pattern of "overbank sedimentation and riverbed incision". Erosion/deposition analysis shows that erosion area is larger than deposition area, and volume of erosion below the benchmark (the navigation reference plane) is larger than the deposition volume above the benchmark.

To explore the empirical reason of these channel changes, hydrological regime changes over last 50 years were examined. Due to the decrease of diversion ability of water and

sediment in Dongting Lake, greater discharge and sediment load passing through the Jianli sub-reach promoted bank erosion in the most meandering part of the Jingjiang reach, which also presents as the bank migration and channel widening. Intensive overbank flows facilitated deposition over riverbanks and undercutting in the riverbed. Large flood contributes to the deposition over floodplain and bars in the channel, but its modification in the riverbed cannot last because of its low frequency.

The impact of human activities such as bank revetment, artificial cutoff, and levee construction were also examined. Bank revetment affected river channel changes through narrowing the channel capacity and providing sediment source. The Shangchewan cutoff event not only temporarily enhanced erosion upstream/ downstream of the cutoff bend, but also prolonged the high flood stage duration. Particularly, this study emphasizes that levee construction plays an important role in the pattern of “overbank sedimentation and riverbed incision”, as it constraints the spread of floodwater and increases flood stage and longer flood duration. As more funds are allocated on the levee construction along the Yangtze River, the impact of levee construction will be enhanced with the levee reinforcement.

Abbreviations and Acronyms

DEM	Digital Elevation Model
FFMI	Flash Flood Magnitude Index
GIS	Geography Information System
GPS	Global Position System
NRP	Navigation Reference Plane
P.R.China	People’s Republic of China
SSC	Suspended Sediment Concentration
TIN	Triangulated Irregular Network
TGP	Three Gorges Project
TGD	Three Gorges Dam
YWCC	Yangtze Water Conservancy Committee

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Chapter 1. INTRODUCTION

1.1 Preamble

For some large rivers the effect of human intervention on river channels has been well documented (Braga and Gervasoni, 1989; Hooke 1995; Gurnell, 1997; Surian, 1999; Fuller *et al*., 2003; Rinaldi, 2003). Human intervention in river catchment includes impoundment construction, sediment mining, bank revetment and artificial cutoff. These activities initiate changes in the hydrology regime and channel conveyance ability, and may reduce channel stability (Knighton, 1984; Shield and Abt, 1989; Simon, 1992; Winterbottom, 2000; Simon *et al*., 2002; Yang *et al*., 2002; Fuller *et al*., 2003; Grant *et al*., 2003; Kesel, 2003; Rinaldi, 2003). It is noticed that the effects of channel changes caused by human activities are more severe than those caused by natural events such as floods, landslides and climate variations (Petts and Amoros, 1984; Surian and Rinaldi, 2003). Changes in river channels will have various environmental and social effects such as causing difficulty in navigation management, flood hazard and the alteration of aquatic and riparian ecosystems. Therefore, a better understanding of the impact on channel adjustments by human intervention is of great importance for river engineering and environmental management.

As the largest river in China, the Yangtze River has for hundreds of years been subjected to a variety of human activities. Already hundreds of years ago (JLAC, 1991; Chen *et al*., 2001a) levees were raised along the Jingjiang reach, which is the most meandering part along the Yangtze River. Since the founding of P.R China, lake reclamation and impoundment constructions have thrived in the river basin for agricultural use and hydropower generation. Also, artificial cutoffs were carried out along the lower Jingjiang reach. At the same time floods occurred more and more frequently and the damage caused by these floods became increasingly severe in the prosperous Yangtze basin, which is the agriculture and industrial base for the entire China (Yin and Li, 1999). This phenomenon is commonly regarded as a result of the intensive human activities along the middle Yangtze River, especially the meandering Jingjiang reach (Lu and Luo, 1997; Yang and Tang, 1998; Pan and Lu, 1999). Lake reclamation and impoundment constructions have substantially changed the hydrological regime in the Jingjiang reach, which resulted in more water and sediment discharge through the mainstream of the Jingjiang reach (Pan and Lu, 1999). Cutoffs in the lower Jingjiang reach have shortened the river length by 78 km, which deteriorated bank erosion along this part of the river (JLAC, 1991).

A few studies have identified the channel changes in the middle Yangtze River due to human intervention (Lu and Luo, 1997; Pan and Lu, 1999; Yin *et al.*, 2004). Their studies mainly used data of discharge and sediment load to examine the hydrologic regime change due to the shortage of historical cross-section observational data (especially after 1987). A holistic research on river channel geometry changes in relation to human activities along the middle Yangtze River is lacking. In particular, few studies have reported the impact of levee construction on the distribution of erosion/deposition in the river channel.

This study focuses on a 108 km stretch of the lower Jingjiang reach (Jianli sub-reach), which is the most meandering and flood-prone stretch in the middle Yangtze River, as an example to examine river channel change since the 1950s. As hydrological survey data have not been published since 1987, channel change in the study reach after 1987 can only be detected on the basis of map materials and GIS technique. In order to reconstruct historical channel change after 1987, channel distribution map (1:100,000; 1951, 1965 and 1975) and navigation channel charts (1:25,000; 1981 and 1997) were employed in this study. DEMs based on the map materials make it also possible to examine the erosion/deposition pattern and volume in the selected study reach.

1.2 Aims and Objectives

By linking DEMs with hydrological survey data, this study aims to reconstruct the historical river channel through examining bank failure, bar development, cross-section changes (cross-section changes and longitude profile changes). This study has three objectives:

1) To examine river channel changes under the constraint of levees on banks;
2) To estimate the location and volume of erosion and deposition in the river channel;
3) To explore factors responsible for channel changes in the study reach.

1.3 Structure of the thesis

Including this chapter, the whole thesis consists of eight chapters. The literature review sketches the theoretical background and previous work on river channel changes. Chapter 3 (Study area) describs the geographic setting, hydrologic regime and human activities in the middle Yangtze River, Jingjiang Reach and Jianli sub-reach. Chapter 4 deals with methods and datasets. This chapter also introduces the process of constructing DEMs on the basis of navigation channel charts. Chapter 5 and Chapter 6 are respectively presenting the results from the analysis of hydrological data and map materials. Chapter 5 examines the cross-section changes at the major stations along the middle Yangtze and the most meandering Jianli sub-reach in the lower Jiangjiang reach. In contrast to Chapter 5, which only describes cross-section changes before 1987, Chapter 6 details channel changes along the Jianli sub-reach from 1981 to 1997 on the basis of map materials (Channel distribution map and navigation channel charts). Chapter 7 attempts to examine the empirical reasons of channel changes in the Jianli sub-reach. The conclusion (Chapter 8) summarizes achievements and limitations of this study and outlines the future prospects in this study field.

Chapter 2. LITERATURE REVIEW

2.1 Theoretical background of channel change studies

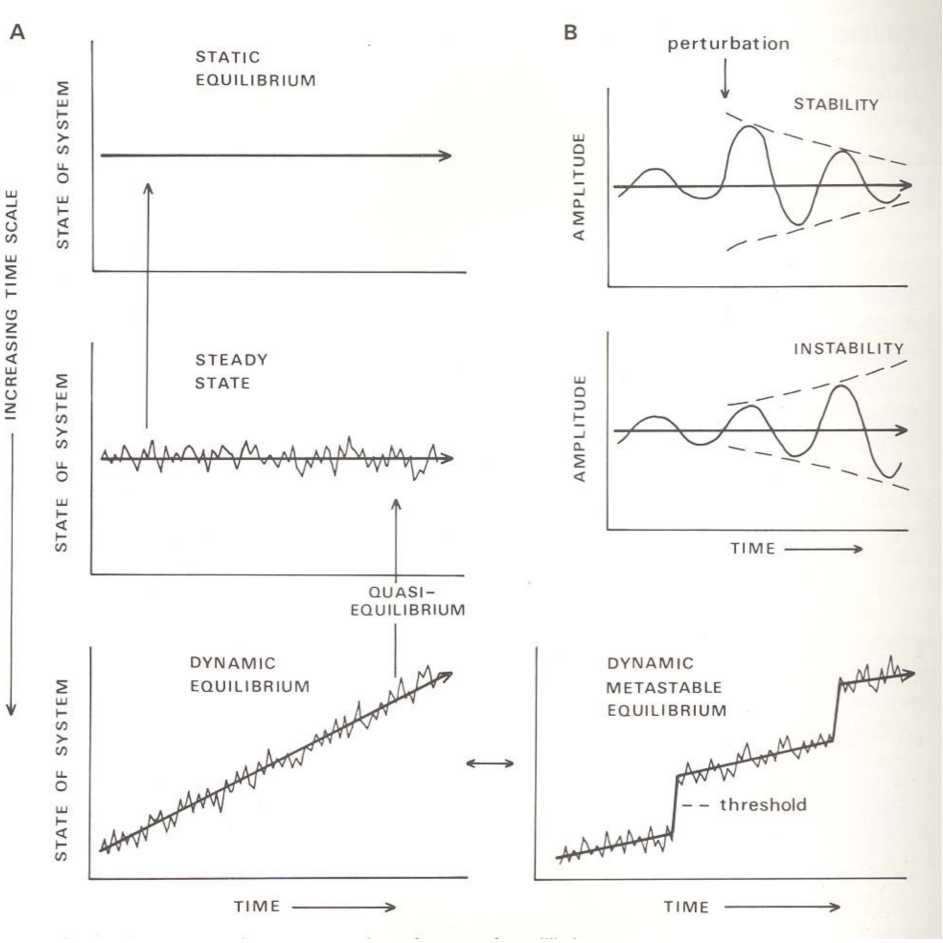
2.1.1 The concept of equilibrium

True stability never exists in natural rivers, which frequently change their position and which have range of discharges and sediment loads. However, natural rivers can be relatively stable in the sense that, if disturbed, they will tend to retrieve their previous state and the perturbation is damped down (Knighton, 1984; Darby and Delbono, 2002).

In geomorphology, the term "dynamic equilibrium" refers to an open system in a steady state in which there is a continuous inflow of materials, but within which the form or character of the system remains unchanged (Leopold *et al*, 1964; Park, 1995). When a river system is observed over a short time period, oscillations about any trend may be so much greater than changes in the trend itself that the system looks like steady-state equilibrium (Fig 2.1b). This tendency toward a steady state is termed "quasi-equilibrium" (Knighton, 1984; Ritter *et al*, 1995) (Fig 2.1a).

Channel sensitivity is the extent the river channel is able to change. It is determined by alterations to the quality and quantity of water flow, by direct modification of the channel and by changes of the area adjacent to the channel (Downs and Gregory, 1993).

Fig 2.1 a. Diagrammatic representation of types of equilibrium. b. Definition sketches of stability and instability in an oscillating mechanical system subject to a perturbation (adopted from Knighton, 1984).



2.1.2 Time scale issue

Rivers can only attain an approximate equilibrium at some suitable time scale between short-term fluctuations and long-term evolutionary tendencies, when the river channel adjusts to external controls (Lane and Richards, 1997; Cammeraat, 2002). Hence, time scale issue was addressed and formed one of the major challenges in the fields of environmental studies. Commonly, time periods can be defined as:

1) Instantaneous time scale ($<10^{-1}$ years);

2) Short time scale (10^1-10^2 years);

3) Medium time scale (10^3-10^4 years);

4) Long time scale ($>10^5$ years).

Channel change in instantaneous time scale cannot make much sense neither in describing channel form change nor understanding channel evolution dynamics. Over the short time scale, the stream transports its load selectively and the temporal pattern of discharge may be thought of as a single entity. This time period is most significant for examining the relationship between the independent variables and certain elements of channel form (Leopold and Maddock, 1953; Sandra, 2000). At the medium time scale, the stream adjusts its internal geometry in such a way that the sediment supplied can be transported with the discharge available, so that material does not accumulate indefinitely. These two time periods (short and medium time scales) are the most relevant as regards channel form adjustment, since mean water and sediment discharge are independent variables to which average channel geometry is related (Winterbottom, 2000; Sandra, 2000). Over longer time periods, geological events such as large climatic fluctuation, tectonic movement became the major controls on channel change, since discharge and load conditions are no longer constant in the mean and adjustment (Knighton, 1984; Lane and Richards, 1997). Most of the fluvial geomorphology studies deal with the channel changes in the short and medium time scales.

2.1.3 Hydrology regime

Water discharge and sediment load, the essence of a river, play important roles in modifying river morphology and planform patterns through space and time, and supporting riverine ecosystems (Pickup et al, 1984; Hickin, 1995; Miller and Gupta, 1999; Chen et al, 2001). The physical processes driving these two important components of river flow downstream provide an effective means of balancing sediment provenance and sediment flux, and control the fluvial geomorphology (Ritter et al, 1995; Moody, 2002). Mobile sand or gravel riverbeds may aggrade or degrade in response to changed conditions of sediment load or water discharge (Bravard and Bethemont, 1989). Along many rivers the addition of water and sediment from tributary sources of variable size produces discontinuous change in the controls, with parallel discontinuities in channel morphology (Leopold and Meddock, 1953; Leopold et al, 1964; Kinghton, 1984; Bogena and Diekkrüger, 2002).

Dominant discharge is defined as the discharge that determines the characteristics and dimensions of a channel, to some extent can be accepted as bankfull discharge with 1-2 year of return time, but not suitable in every river (Leopold *et al*, 1964; Knighton, 1984; Ritter *et al*, 1995). Dominant discharge has a consistency in the frequency with which bankfull discharge occurs along stream. Similarly, bankfull discharge also has synchronous frequency with the most effective discharge, which accumulatively transports most sediment. But the effectiveness of large-magnitude but low frequency floods is significant on river channel form changes, especially in monsoon-dominated area (Kale and Hire, 2003). Therefore, Flash Flood Magnitude Index (FFMI) is used to evaluate the probability of geomorphologic changes in the river response to a flood with great magnitude but low frequency, if long-term discharge records available (Kochel, 1988).

Sediment flux is an essential element to shape river channel geomorphology as it affects the stress of water flow imposing on river channel. Pickup et al (1984) summarized three types of relationship between sediment and channel characteristic: channel shape VS perimeter sediment, channel bed VS bank sediment and channel planform VS the size of the bed material. On the basis of the dominant mode of sediment transport, Schumm (1963) subdivided channels into three types using M (percentage silt-clay) as his criterion: (i) bed-load channels ($M \leq 5$), (ii) mixed-load channels ($5 < M < 20$), (iii) suspended –load (or wash-load) channels ($M \geq 20$).

The stream erodes sediment from its bed to keep pace with an increasing equilibrium rate, but there may be limits on sediment availability, either because of supply or resistance. During floods, the increasing in flow velocity and shear stress greatly increases sediment transport capability. When the sediment supply has exceeded the transport capacity, the river channel would undergo bed aggradation with variable bed armouring (Lisle and Madej, 1992). When major floods have low sediment content, extensive erosion rather than deposition may occur (Bukham, 1972).

According to Surian (1999), as a consequence of decreases in the flows and sediment supply, Piave river in the Eastern Alps has undergone a 35% channel width narrowing and the planform pattern of some reaches changed from braided channel to wandering channel. Kale (2002) reviewed the rivers in India with an array of discharges, of which most were subject to morphology changes due to high-magnitude floods.

2.1.4 Channel geometry

Channel geometry refers to the three dimensional form of the channel. The adjustment of channel geometry to external controls can be considered in terms of four degrees of freedom: 1, Cross-sectional form—the size and shape of a channel in cross-profile either at a point or as a reach average; 2, Bed configuration—the distinct forms molded in the bed of particularly sand- and gravel-bed streams; 3, Planimetric geometry or channel pattern—the two–dimensional form of the channel when viewed from above, the commonest subdivision being into straight, meandering and braided. 4. Channel bed slope—the gradient of a stream at the reach and longitudinal scales, where the latter also refers to the overall shape of the longitudinal profile (Knighton, 1984).

Adjustments to cross-sectional form and channel pattern receive greater emphasis as means of achieving equilibrium, and more attention focuses on the dynamics of the adjustment process than on the stability of a particular channel shape or profile. The shape of the cross-section of a river channel at any location is a function of the flow, the quantity and the character of the sediment transported through the section, and the character or composition of riverbank and riverbed (Leopold *et al.*, 1964; Knighton, 1984). When a river is subject to high flood discharge or altered hydrologic regime, cross-section form is one of the most adjustable opponents of channel geometry, at least in the width dimension. Width and mean depth give the gross dimensions of the channel, and width and mean depth (W/D) is commonly used as index of channel shape even though it is also not the most appropriate. The width/depth ratio of the cross-section controls the distribution of flow in the channel, especially in the meander bends (Markham and Throne, 1992).

In order to classify channel pattern, sinuosity is defined as

S=Channel length / straight-line valley length (Leopold and Wolman 1960; Leopold, 1964; Knighton, 1984; Ritter *et al*, 1995). Normally, it is considered as meandering river if river has a sinuosity of 1.5 or greater, straight channel if below 1.5 and braided channel if excess 4.0 (Knighton, 1984).

The longitudinal form has historically been a primary interest of geomorphologists but it is the least changeable component and can properly be regarded as an additional constraint on more adjustable ones (Knighton, 1984; Starkel, 1995). The longitudinal profile of a stream describes the way in which the stream's elevation changes over distance. In general, local topography, bedrock features, change in bed material, etc modify the longitudinal profile, which will tend to be steeper on harder rock types and flatter when the streambed is less resistant to erosion (Gordon et al, 1992).

2.2 Previous studies on river channel change

2.2.1 Methods and data sources applied in previous channel change studies

Studies at various time- and space-scales have attempted to understand and explain river channel change, a long-term aspect of landform behavior (Braga and Gerasoni, 1989; Bravard and Bethemount, 1989; Mcewen, 1989; Stuart and Keith, 1997; Ashmore *et al*, 2000). In order to study channel change at the long time scale and medium time scale, sediment cores and archaeological sites are commonly used to analyze channel planform change, riverbed change and types of channel deposits (Brown, 1995; Starkel, 1995; Walling, 1995; Owens et al., 1999; Brewer and Lewin, 1998; Brown et al, 2001; Couper et al, 2002; Rãdoane et al, 2003). For instance, in the Middle Trent, scholars worked on the data from gravel pits, archaeological sites and documentary source and acquired abundant structural evidence of changes in channel pattern and channel type since the 11th century AD (Brown *et al*, 2001). To investigate overbank sedimentation rates and sediment sources in the catchment of the River Ouse, UK, seven floodplain sediment cores were tested with ^{137}Cs and ^{210} Pb dating technology to estimate average sediment accumulation rates for the last ca. 30 and 100 year (Owens *et al*, 1999).

Historical records, including documents, survey notes, maps and photographs, can also provide valuable information about channel changes in a shorter time scale (Gurnell, 1998; Warner, 2000; Winterbottom, 2000; Daba *et al*, 2003). Based on historical maps and aerial photographs, Brewer and Lewin (1998) have examined channel changes in two time scales (2.5 years and 150 years) in the River Seven, mid-Wales. Likewise, Gurnell

(1997) used historical maps and air photographs supplemented with GIS, to identify the channel change of the same river over 115 year period and over 50 years, respectively, and drew a similar conclusion on spatial and temporal trends of the same river stretch in two different scales. With the development of the technique of remote sensing and GIS, more and more remote sensing imageries were involved into the study of fluvial geomorphology regarding quantifying and predicting erosion, change of topography, and channel change in fluvial basin in short time scale (Chappell *et al,* 2003; Daba *et al*, 2003; Franklin and Wulder, 2002; Henry *et al*, 2002; Lane *et al*, 2003; Martinez-Casasnovas *et al*, 2003; Poole *et al*, 2002; Rippin *et al*, 2003).

It is worth to note that due to the varying quality and accuracy, small scale maps haven't been adequately employed in fluvial researches so far. Particularly, the shorter time period one studies, the greater difficulty the study has in identifying channel changes which exceed the errors incurred in information extraction from the photographs and registration to a common map base (Gurnell, 1997). In contrast, despite their snapshot character, fragmentation of records and other limitations, big-scale maps consist of considerable details of river channel changes, which are unattainable in small-scale maps.

One typical example of using historical maps in recent studies is Pišút's research in the Danube River. Channel adjustments of the Danube River were reconstructed on the basis of historical river maps for 1712-1886, the period preceding mid-course channelization. Thirteen local maps were converted to the same scale of topographic map (1: 50,000) in the1950s to reconstruct channel planform changes of the pre-channelized Danube in

Bratislava and to examine the impact of floods and human works on the channel changes (Pišút, 2002).

Also, many landscape models have been developed over the past decades for reconstructing the historical channels (Yin and Wang, 1999; Hancock and Willgoose, 2001; Finlayson and Montgometry, 2003; Khan and Islam, 2003; Rippin *et al*., 2003; Martínez-Casasnovas, 2003). As a Digital Elevation Model (DEM) can imitate landform surface variability well and provide the opportunity to measure and monitor morphological change, they have been frequently used in previous studies to simulate the channel evolution procedure in the last decades (Sandra, 2000; Warner, 2000; Brasington and Smart, 2003; Rinaldi, 2003). Using the elevation data from a ground-based three-dimensional tachometric survey in two reaches of the River Nent, UK in two periods, DEMs in each reach and for each survey period were built up to elucidate the relationship between process and the form of channel change operating at different spatial and temporal scales (Chappell, 2003). Lane *et al* (2003) developed a DEM coupling the use of remote sensing for channel change detection (erosion and deposition volumes) in a wide, braided, gravel-bed river. The rates of channel incision and sediment production were computed from the subtraction of multi-temporal DEMs. Aerial photograph and orthphotos were also employed to map the gully erosion and determine erosion rates with DEMs (Martinez-Casasnovas, 2003).

Usually geomorphologists use three methods to generate DEMs according to the required scale, quality and resolution: 1) radar interferometry for scales higher than the 1/1000^{e}, 2) the Global Position System (GPS) if the relief is very marked or if many obstacle exist, 3) digital photogrammetry with various resolutions assording to the scale of photographs (Henry *et al*, 2002; Mount *et al*, 2002; Brasington and Smart, 2003). However digital photogrammetry and remote sensing images cannot provide the bathymetric information under the water. With the help of GIS, historical bathymetric charts can help make up of the shortage of historical bathymetric data for DEM under the water bodies, although source errors and uncertainty in the charts cannot be eliminated (Van Der Wal and Pye, 2003).

Henry et al (2002) recommended small–format and low–altitude aerial photos to generate a DEM in mountainous areas. In their study, in-situ taken aerial photos were applied to the 3D modeling of the Super-Sauze earthflow and its environs. Another successful application of aerial photos is the 3D mapping of the Nyack flood plain of Middle Fork Flathead River, MT, USA. On the basis of aerial photo interpretation and the identified relationships among element-types, elevation, and preferential ground-water flow paths, Poole *et al.* (2002) developed a quantitative, three-dimensional model of surface and subsurface geomorphology across the entire flood plain to investigate the influence of flood-plain geomorphology on spatial-temporal patterns of surface and ground-water flow.

However, resolution effects of DEM remain a factor of uncertainty in many hydrological and geomorphologic modeling approaches. Schoorl *et al.* (2000) found out that when using DEM elucidates the processes of erosion and sedimentation, erosion predictions increases with coarser resolution. Heesom and Mahjoubi (2001) tested the effect of grid resolution and terrain characteristics on data from DTM and found that both increasing the grid resolution and varying the characteristics of the terrain will affect the accuracy of any derived data. But Lane *et al* (2003) suggested that even though point precision is not as good as traditional cross-section survey, this estimation of volume changes based on DEM still could produce more reliable erosion and deposition estimates as a result of great improvement in spatial density.

2.2.2 Studies on channel planform changes

Changes in channel planform take place by erosion of the banks, by deposition within the channel and by meandering cutoff and channel migration (Hooke, 1995; Gilvear *et al*., 2000; Richardson, 2002; Darby and Delbono, 2002; Frothingham and Rhoads, 2003; Rinaldi, 2003). Air photos and field survey show high rates of channel migration (about 33 m/a) and cutoffs on meandering section in the Luangwa River, Zambia (Gilvear *et al*., 2000). Besides bed incision, channel narrowing appeared the main alluvial rivers of central Italy, 38% of analyzed reaches experienced a narrowing greater then 50% of the initial channel width (Rinaldi, 2003). According to the sequential changes in the position of bank lines, four types of changes took place in the Subansiri river channel, India: (1) alteration of the direction of flow after neck cut-off, (2) widening of a channel due to bar development, (3) development (and subsequent abandonment) of anabranches, and (4) progressive migration of meander bends (Goswami *et al*., 1999).

To some extent, all the channel planform changes are accompanied with bank erosion (Hooke, 1995; Winterbottom, 2000; Couper and Meddock, 2001; Dapporto *et al.*, 2003). In a long time scale, bank erosion is a basic component of meander formation, lateral channel migration and movement for sediment throughout the drainage basin. In a short time scale, bank erosion put an effect on the riparian and floodplain structure and the fertile agricultural land of the flood plain (Couper and Maddock, 2001).

Many focused on the main mechanisms of failure and retreat, their spatial distribution and their causes (Goswami *et al.*, 1999; Dapporto *et al.*, 2003; Winterbottom and Gilvear, 2000; Yue and Yu, 2002). Couper and Maddock (2001) suggested that three mechanisms, mass failure, fluvial entrainment and subaerial weakening and weathering, interact as the primary mechanism of bank erosion. Winterbottom and Gilvear (2003) concluded decisive factors affecting the rate and distribution of bank erosions include: 1) bank height, 2) height of under cutting, 3) river bank slope, 4) river bank sediment type and structure, 5) river bank vegetation, 6) channel slope, 7) presence of adjacent flood embankment,8) presence of a lateral gravel bar adjacent to the river bank, 9) channel mobility restricted by bedrock.

The ability of a stream to modify its channel pattern depends partly on the sensitivity of bank material to erosion (Knighton, 1984; Lisle and Madej, 1992; Couper *et al*, 2002). Composite (silt and clay) stream bank is very susceptible bank type (You, 1987). After examining 6 types of riverbanks, Dapporto et al (2003) found out the fine-grained banks are susceptible to slab-type failure, while composite banks are prevailed with cantilever failures.

Bank erosion is also one of the principle means of sediment supply to streams. According to Simon et al. (1991), failed bank material was partly removed by river flow and deposited as bed material or dispersed as suspended load. Other fluvial material remained deposited along the toe of the bank as intact blocks. Severe bank erosion was observed in the Yangtze River basin and became one important sediment supply to the river channel. According to Xu *et al.*'s research in Yangtze river, from Wuhan to Nanjing bank collapse happened in 22% bank line of 1479 km in length in 30 years, The collapsed area is 89.1 km^2, if the average elevation distance between bank and water surface is 3 m, it is estimated that 267×10^6 m^3 (about 708×10^6 t) of sediment were deposited in the channel of lower Yangtze reach, which is almost equal to the total amount of deposition (770.6×10^6 t) in this reach (Xu *et al.*, 2001).

Channel planform changes can be also represented as the changes in channel sinuosity in the meandering rivers. Timár (2003) reconstructed the river channel of Tisza River and found out the sinuosity changes of the river is not correlated with water discharge and sediment load, but also with its physical setting like the position of faults and subsidence anomalies.

2.2.3 Studies on river cross-section change

Any important adjustment of channel form and floodplain development is reflected in the bankfull capacity of the cross-section and the relationship of floodplain sedimentation and construction to channel pattern (Pickup and Spring, 1984; Garcia, 1995; Hickin, 1995; Niekerk *et al.,* 1999; Inbar, 2000; Emmett and Wolman, 2001;Dollar, 2002; Moody and Troutman 2002).

Variables of cross-section are of great importance for hydraulic geometry and channel geomorphology studies. Analysis of cross-sections in the lower Rhône River demonstrated the dominance of channel incision over a century in the river (Antonelli et al, 2004), which is consistent with the study of Arnuad-Fassetta (2003). Although hydraulic data (boundary shear stress and stream power) employed in the study have no direct relationship with the channel deformation, channel geomorphology bound with these hydraulic controls locally regulate the incision rates. Cross-sections in the Raba River, Poland showed 3 m of river incision of occurred in the last century, this is associated with the increase of stream power and decrease of bedload resulted from river control works and gravel extraction (Wyżga, 1991).

Cross-sections were also employed to examine the relationship between channel change and flood occurrence. Stover and Montgomery (2001) analyzed 45 years of cross-section data along the Skokomish River, and figured out that the increased flooding on the mainstream of this river without an increase in peak discharge resulted from the reduction of channel conveyance due to aggradation in the riverbed.

Longitudinal profiles in rivers can be used to monitor changes in bed topography response to flood event and human activities. Longitudinal profiles survey undertaken during the construction of Miribel Canal, upstream of Lyon (1884-1858) demonstrate a tilting of riverbed along a 20 km reach (Bravard and Bethemont, 1989). With successive longitudinal thalwag profiles in this gravel-bed river, Madej (1999) monitored riverbed topography changes following floods and associated large sediment inputs in Redwood Creek basin, northwestern California. By comparing the longitudinal profiles of different years, sediment mining was claimed as the dominant factors of bed incision (up to 9 m bed-level lowering) in alluvial rivers of Tusacany, central Italy (Rinaldi, 2003).

2.2.4 Studies on the impact of flood disturbance

Flood event was a traditional examining topic when discussing channel geomorphology because they alter discharge and sediment load in river and affect the channel geometry not only during the events but also in their relaxation time (Warner, 1995; Bathurst *et al.*, 2002; Li and Ni, 2001; Moody and Troutman, 2002; Polyakov and Nearing, 2003; Xu, 2002; Xu and Cheng, 2002). Gupta (1988) has summarized main effects of large floods are widening of channel; erosion of bars; scouring of flood plains, coarse deposition within the channel etc. After a flood along a braided river in arid-region area, channel width increased downstream while channel aggradation also occurred along the wide and braid reaches (Merritt and Whol, 2003)

Channel instability is widely revealed associated with floods with great magnitude (Park, 1995; Liu and Wang, 1999; Brooks and Lawrence, 2001; Uribelarrea et al., 2003). Major floods cause adjustment to the fluvial system after exceeding the limiting threshold of the former geomorphic system, and hence new long-term equilibrium condition develop.

Some have found out that floods with low frequency but great magnitude have a decisive effect on the modification of the fluvial landform (Gupta, 2000; Inbar, 2000). Along the lower Eel River, channel widening from extensive bank erosion was the dominant geomorphic change along the lower Eel River during major floods, while the tributaries of Eel River endured rapid aggradation in the channel valley followed by immediate downcutting (Sloan et al., 2001). Kale (2002) noticed that in tropical monsoon area, large floods not only temporally affect the forms and behavioral characters of river, but also leave a lasting effect on other characters, such as the scouring/deposition in the floodplain.

The effectiveness of a flood in shaping the river channel depends upon the force exerted, the return period of the event, and upon the magnitude of the constructive or restorative processes, which occur in the intervening intervals (Inbar, 2000). McEwen (1989) presented that an extreme event of high recurrence interval (in excess of 100 years) would have a major initially disruptive impact on river channel planform in an upland basin in Scotland, given that room is available for expansion of the channel's active area and that threshold for disruption are surpassed (in term of competence to transport available sediment), while, moderate discharges (10-50 years recurrence interval) appear to be more important in returning the channel to a quasi-equilibrium form than disrupting it. However, after comparing data from gravel pits, archaeological sites and history records, Brown et al (2001) found that there is no constant relationship between flood magnitude and channel form change along the Middle Trent in the late Holocene. In India, the incised channel form in the Tapi River enhances the role of large floods by reducing the W/D ratio and by increasing the velocity as well as the energy per unit area (Kale and Hire, 2003).

2.2.5 Studies on human impacts on river channel change

Human intervention rearranges the sediment and water transportation and distribution in river course and drainage basin, and hence changes the dynamics of channel evolution (Petts and Amoros, 1984; Downs and Gregory, 1993; Ashmore *et al.*, 2000; Hudson and Kesel, 2000; Surian and Rinaldi, 2003). The common human disturbances in river catchments include landuse change, impoundment construction, channelization.

Landuse change

Forest clearance and overgrazing causes an acceleration of runoff and sediment delivery to river channels (Pasternack *et al.*, 2001; Brannstorm and Oliveira, 2001). In Europe, cutting of trees on the Vistula floodplain accelerated the lateral migration of the river channel and induced aggradations. Extensive agriculture and higher density cart-roads during the 16th to 19th centuries caused more frequent flooding and higher sediment loads in the river basin (Starkel, 1995). In China, the desertification in the northwest China yields abundant sediments into the river basin and sand/dust storms. Yellow River is famous for its high SSC, which gives the river the yellow color. The high sediment concentration in the river blocks the river channels and makes the river wander and the riverbed and the water level unstable (Xu, 2002).

In Yangtze River, it was noticed that widespread excessive cutting of trees since 1949 has reduced natural water storage capacity and increased the soil run-off into rivers in the Yangtze basin (Li *et al*., 2000). Deforestation and cultivation of hillsides in the upper Yangtze basin exacerbate the loss of soil and increase sediment load (Chen *et al*., 2001; Yin and Li, 2001; Yang, 2002), these sediments are either settle down behind dams or transported to lower reach, hence modifies the channel capacity and further alters channel geometry.

Impoundment construction

Reservoir is one of the most frequently used structural means for flood prevention along rivers. The basic function of a reservoir is to provide detention of flood runoff and to release it in a regulated manner. The result of this function is the attenuation of the flood hydrograph, where the peak and the shape of the hydrograph, together with the resulting downstream water levels are transformed by the reservoir (Harmancioğlu, 1994)

Marked changes in channel form have been observed downstream of reservoirs and dams whose construction tends to reduce flood peaks and sediment load (Greenwood *et al*., 1999; Shileds *et al*., 2000; Cluett and Radford, 2003; Fang *et al*., 2003). Channel depth and in particular width can respond rapidly to changes in the dominant controls– water discharge and sediment load.

Hydrogeomorphic changes-changes in discharge and sediment–transport regimes-induces by dams and their operation are only part of the equation for predicting downstream impacts. The geological setting of dams within the watershed also contributes, both in the sense that geology strongly influences the distribution of water and sediment sources within the watershed and because potential adjustments of the downstream channel are strongly influenced by the geologically mediated disturbance history (Birch *et al.*, 2000). Battella *et al.* (2004) investigated hydrological changes resulted from the impoundment construction in Ebro River. Reservoirs have induced the reduction of flood magnitude, without marked changes in annual runoff.

Dam construction alters the downstream hydrological regime and affects the stability of river channel through adjusting water discharge in drought and flood season (Juracek, 2000; Simon *et al.*, 2002; Surian and Rinaldi, 2003). Construction of reservoir in the upper stream retains sediment (especially bedload) and results in reduction of sediment budget (Yang *et al.*, 2002; Kesel, 2003). The decrease in bedload material would accelerate channel incision (Steiger *et al.*, 1998). For instance, Fort Peck Dam on the Missouri river initiated the 3.6m riverbed degradation and bank failure at downstream (Grant *et al.*, 2003).

Channelization

Channel embankments as well as the modification of channels by confining and straightening result in simultaneous down-cutting and narrowing of river channels (Gregory, 1977; Taylor and Asce, 1978; Winterbottom, 2000; Rinaldi, 2003). Remarkable channel narrowing in Piave River was resulted from the decrease in water flows and sediment supply because of human intervention; some reaches even underwent channel planform changes from braided channel into wandering channel (Surian, 1999).

Flood embankment construction in the mid-1800s caused a significant narrowing in European rivers (Winterbottom, 2000). In Italy, a flood defense system made of earth embankments, both on the left and south bank, borders the Po river channel for 2290 km, the whole embankment system has generally an irregular character and was built relatively recently upstream of Piacenza, but is older and more continuous eastward from this town (Braga and Gervasoni, 1989).

As a usual means of river control work, the impact of cutoff in the meandering river has been broadly discussed (Shield and Abt, 1989; Hooke, 1995; Fuller et al, 2003). Cutoffs at meander bend change the flow direction and disturb the equilibrium in river channel morphology and ecology system (Shield and Abt, 1989). Cutoffs enlarged slope and stream power in the river channel of the Lower Mississippi River (Biedenharn *et al.*, 2000). Cutoff events also deteriorate bank failures along the river (JALC, 1991).

Sediment dredging affects riverbed instability because of sediment removal in the river channel (Simon, 1992). Bank revetment and levee construction to prevent flood and control the bank erosion halt the natural channel evolution, and enhance the channel incision in the riverbed (Knighton, 1984; Yin and Li, 2001).

In fact, river channel change cannot be attributed to any single human activities. Normally, several human activities will act on the river channel at the same time. For instance, due to human intervention such as sediment extraction, dams and channelization, incision and narrowing in Italian rivers are more intense immediately after the disturbance during the past 100 years (Surian and Rinaldi, 2003). The dam construction and industrial gravel extraction in the Garonne River also has accelerated channel incision, because of the decrease in bedload material in the channel (Steiger *et al.*, 1998).

Chapter 3. STUDY AREA

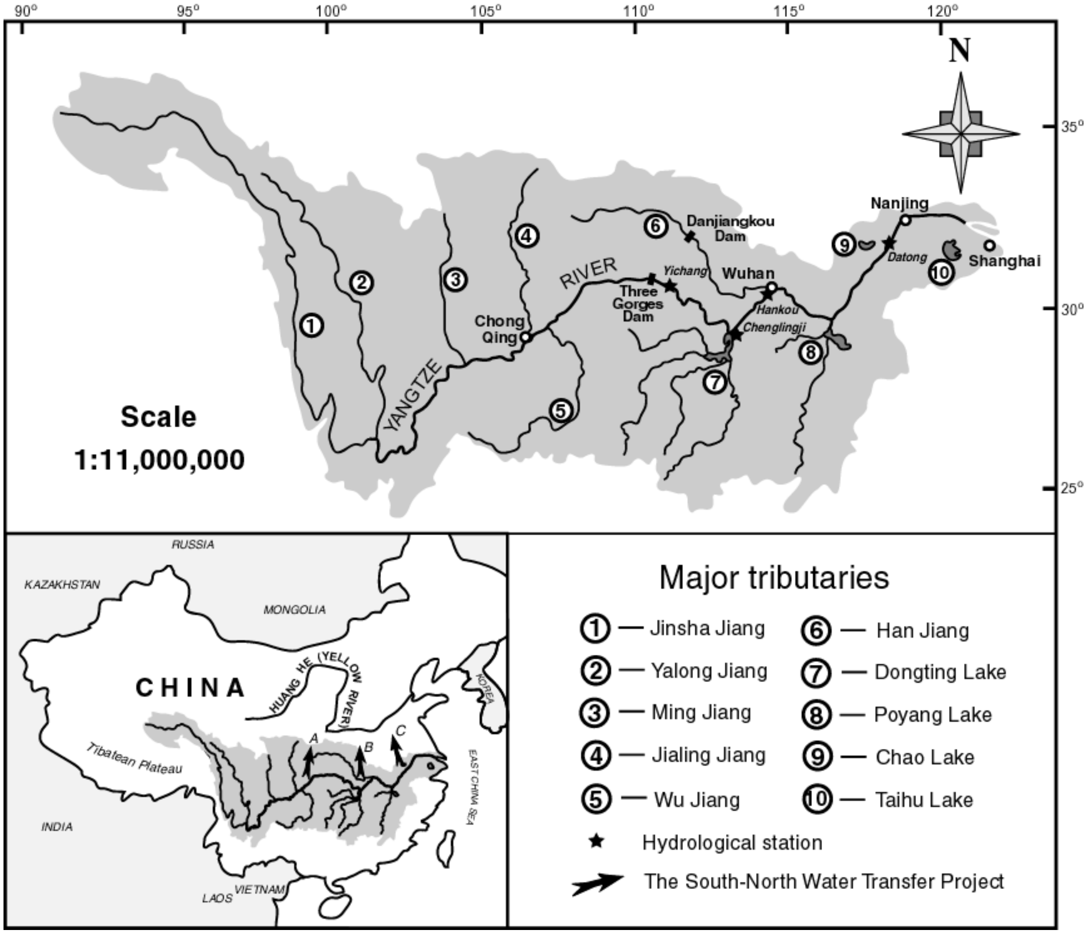
3.1 Geographic setting

3.1.1 The Yangtze

The Yangtze River (Changjiang) is 6300 km in length, the longest in Asia and third longest in the world after the Amazon of South America and the Nile of Africa. The Yangtze drainage basin covers 1,800,000 km^2 of land, making up 18.92 % of China's total area (see Figure 3.1). The river has over 3,600 tributaries in the drainage basin but the principal tributaries are Yalong Jiang, Jialing Jiang, Min Jiang, Tuo Jiang, Wu Jiang, Han Jiang and Dongting Lake, Poyang Lake, Chaohu Lake and Taihu Lake (Xia *et al*., 2001; Figure 3.1).

The Yangtze River can be divided into the upper, middle and lower Yangtze reaches on the basis of geology, climate and geomorphology of the river. The upper Yangtze is more than 4300 km long from the source to Yichang, and has a total drainage area of about 1000,000 km^2. The middle reach starts from Yichang, at the end of the Three Gorges reach, to Hukou, the outlet of Poyang Lake on the Yangtze River. Three large inputs of the main stream in this section are Dongting Lake, the Hanjiang River and Poyang Lake (Figure 3.1). Below Hukou, the final 830 km course constitutes the lower Yangtze River with a total drainage area of 120,000 km^2 (CWCC, 2000; Tang and Xiong, 1998). Near its mouth, the river with its large water and sediment discharges has built a large Yangtze delta, which is over 50,000km^2 including the sub-aqueous delta (Chen *et al*., 2001b).

Figure3.1 The Yangtze River (Adopted after Chen et al., 2001b).

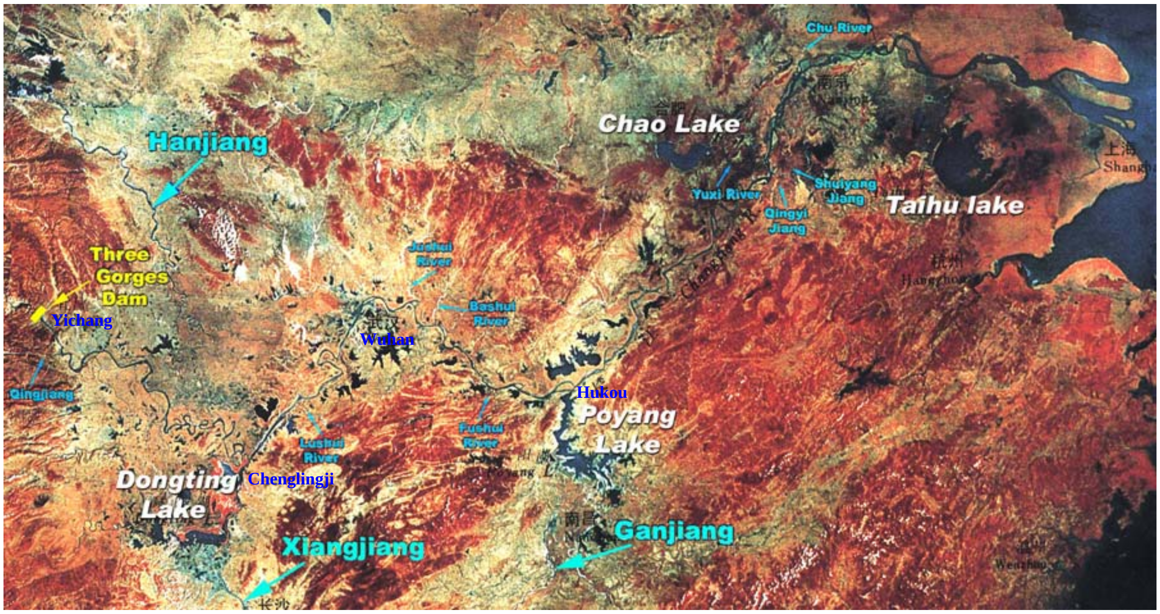


3.1.2 The middle Yangtze River

The middle reach of the Yangtze River is defined as the stretch from Yichang to Hukou, 948km in length and the total drainage basin area is 680,000 km^2. The grade of the river trunk in the middle reach is much smaller than the upper reach as it runs out of canyon region to the fluvial plain. Numerous lakes have formed in the fluvial plain since it is flatter than the upper mountain area (Figure 3.2). In addition, three nodes (Shishou, Luoshan and Hankou) in the middle Yangtze River promote the development of braided reach. Many islands have developed in the braided channel. According to You (1986), there are 71 stable islands in the channel of the middle Yangtze River.

As the Yangtze pours out of the incised river valley in the upper stream, the channel of middle Yangtze is wider and deeper than the upper course, with a width generally in the range of 2-7 km and depths of 6-15 m (Tang and Xiong, 1998; YWCC, 2000; Chen *et al.*, 2001). The middle Yangtze River becomes the sink of sediments from upper stream as water velocity slows down in the middle reach. Every year 0.2 billion tons of sediment has been transported into Dongting Lake and silt up, which has resulted in the shrinkage of the lake (Du *et al.*, 2001b). Besides, the river channel changes into a meandering pattern from the upper Yangtze rock section.

Figure3.2 Topography of the middle and lower Yangtze River.



The middle Yangtze River consists of 2 sections: first section from Zhicheng (very close to Yichang) to Chenglingji (also called the Jingjiang reach) and the second from Chenglinji to Hukou (the central gray portion in Figure 3.2). The Jingjiang reach was named after the city “Jingzhou” and its river pattern consists of meanders, while the lower section from Chenglinji to Hukou is braided as many islands and anabranches have developed in the channel. Dongting Lake and Poyang Lake lie in the Jingjiang reach and Chenglingji-Hukou reach respectively (Figure3.2). These two large lakes are very important in diverting floodwater during the flood season in the middle Yangtze Basin. Therefore any changes in the lake surface and lake capacity in these two lakes would induce great potential of flood disaster in this basin. It can be seen from Table 3.1 that the lake area of Dongting Lake and Poyang Lake decreased greatly from 4350 km^2 in 1949 to 2623 km^2 in 1995 and from 5200 km^2 in 1949 to 3840 km^2 in 1995, respectively (Table 3.1).

Table 3. 1 Decrease of area and volumes of Dongting Lake and Poyang Lake (adopt after Yin and Li, 2001). The location of Chenglingji and Hukou are indicated in Figure 3.2

Year	Dongting Lake			Poyang Lake		
	Water level at Chenglingji(m)	Area (km^2)	Volume ($10^8 m^3$)	Water level at Hukou (m)	Area (km^2)	Volume ($10^8 m^3$)
1949	33.5	4350	293	21	5200	***NA***
1954	33.5	3915	268	21	5050	323
1971	33.5	2820	188	***NA***	***NA***	***NA***
1977	33.5	2740	178	21	3840	262
1995	33.5	2623	167	***NA***	***NA***	***NA***

3.1.3 The Jingjiang reach

From Zhicheng, 60 km away from Yichang, to Chenglingji is the Jingjiang reach, which is famous for the Great Jingjiang Levee. This reach is 347 km long and cross through

Jianghan plain to the north and Dongting plain to the south. At the point of Ouchikou, which is the junction of Ouchi River and the Yangtze River, the Jingjiang reach was divided into the upper Jingjiang (from Zhicheng to Ouchikou, 171 km long) and the lower Jingjiang (from Ouchikou to Chenglingji, 176 km long). The upper Jingjiang reach has a relatively straight and stable river channel with mid-channel bars in the meanders, while the lower Jingjiang reach is known for its meanders with a high degree of sinuosity. In the late-1960s and early 1970s, after artificial cutoff projects were carried out at Zhongzhouzi bend, Shangchewan bend and Santanzi bend, the sinuosity reduced from 2.83 to 1.93 (YWCC, 2000).

The north bank of the Jingjiang reach is connected with Jianghan plain, which is one of the most important industrial and agricultural bases in China. Southern bank of the Jingjiang reach is connected with Dongting Lake district, the most important retention area along the Yangtze River. The Jingjiang reach and Dongting Lake constitute a giant river net system in the middle Yangtze Basin, ranging from northern latitude 28°30’ to 30°30’ and eastern longitude 111°30’ to 113°30’ (Zhang *et al.*, 2000). The lake also admits other four river’s floods from the drainage area in Hunan province, namely Xiang River, Zi River, Yuan River and Li River (Tang and Xiong, 1998).

The texture of the riverbank in the Jingjiang reach is composed of an upper layer of the fine-grained phase and a lower, coarser bed phase. The thickness of silt/clay is greater than that of sand/gravel. The percentage of silt/clay of riverbank is 92% in upper Jingjiang and 76% in lower Jingjiang reach, respectively (You, 1996). Moreover, hilly land on the southern bank is 5 m to 7 m higher than the surface of north bank (JLAC, 1991).

3.1.4 The Jianli sub-reach

The Jianli sub-reach in the lower Jingjiang reach is selected as an example in this study to elucidate channel changes in the middle Yangtze River over the last 50 years. The Jianli sub-reach starts at Tashiyi and ends at Chenglingji. It was 137 km in length before the Shangchewan cutoff at the end of the 1960s and early 1970s, which shortened the river length by 29 km. The north bank belongs to Jianli County, while the south bank belongs to Huarong and Yueyang counties (JLAC, 1991). The Jianli sub-reach is located in the most distinctive meandering part of the middle Yangtze River and joins with the mouth of the Dongting Lake at the end of the reach.

It crosses the Jianghan fluvial plain, which consists of loose sedimentary stratum with upper cohesive fluvial silt layer and basal fine sand layer (Yang and Tang, 1998). This favours the development of meanders. The amplitudes of meanders range from 20 to 40 km. The Jianli sub-reach is regarded as the most dangerous reach along the Yangtze River during flood seasons because of the susceptible bank conditions and the fragile foundation of levee construction along the banks (JLAC, 1991).

Wandering meanders in the Jianli sub-reach formed in 1500-1550 A.C (JFPH, 1996). There once were a lot of oxbow lakes in Jianli County. Meanders in the Jianli sub-reach are, namely, Jianli, Damazhou, Jingjiangmen, Xiongjiazhou, Qigongling and Guiyinzhou, Shangchewan bend that was cutoff in 1971. The sinuosity of each bend is listed in Table 3.2 below. These meanders experienced severe bank failure. The bank at Damazhou bend retreated by 110 m from 1952 to 1972, while the bank collapse rate at Chibakou bend was 70 m/year (JLAC, 1991).

Table 3.2 Sinuosity of each meander along the Jianli sub-reach (Data collected from YWCC, 1965-1975).

	Jianli	Damazhou	Shangchewan	Jingjiangmen	Xiongjiazhou	Qigongling	Guanyinzhou
1965	**1.65**	**2.35**	**5.07**	**1.84**	**1.81**	**3.27**	**3.18**
1975	**1.62**			**1.6**	**1.98**	**3.19**	**3.14**

Dongting Lake has a complex relationship with the main trunk of the Yangtze (the Jianli sub-reach). Dongting Lake acts as the “kidney” of the Yangtze River, as it receives the floodwater from the mainstream during flood season and mitigates the flood damage. Dongting Lake has lost half of its storage capacity and lake area since the founding of P.R.C. The shrinkage of Dongting Lake resulting from the lake reclamation induces the higher water discharge and sediment load in the Yangtze main stem, due to reduction of water diversion ability in Dongting Lake (Pan and Lu, 1999). Fang Zhong (2001) suggested that the reduction of lake capacity of Dongting Lake directly triggered the high frequent Yangtze floods. Also, during the flood season, the retention at the joint point of Dongting Lake and the Jianli sub-reach may lead to a longer flood retention time and higher flood level. Higher water level in the lower Jingjiang Reach promotes the siltation downstream of Chenglingji at the mouth of Dongting Lake (Li and Ni, 1998).

3.2 Hydrological regime

3.2.1 The middle Yangtze River

The annual Yangtze discharge increases as the drainage basin area expands downstream. The recorded data indicate an increase in discharge, from 4.4×10^{11}m^3 at Yichang, which is the uppermost gauge station in the mainstream of the Yangtze River, to 7.12×10^{11} m^3 at Hankou and to 8.19×10^{11} m^3 at Datong (Tang and Xiong, 1998). In the middle Yangtze River, water discharge in the main stem varies because of the interruption of Dongting Lake, Poyang Lake and Hanjiang. Basically, the water discharge in the middle Yangtze Basin increased from upper-stream to downstream. In Table 3.3, mean annual runoff is 331×10^9 m^3 at Jianli, 641×10^9 m^3 at Luoshan and 701×10^9 m^3 at Hankou, respectively. This can be related to the input of the numerous tributaries in the catchment.

The long-term data in Table 3.3 also show that the suspended sediment load at Yichang at the entrance to the middle Yangtze averages 5.26×10^8 t/a, whereas at Hankou of Wuhan City, it is 4.3×10^8 tons per annum. This indicates that every year 1×10^8 tons of silt is deposited in the Jingjiang reach of the Yangtze and in Dongting Lake (Tang and Xiong, 1998; Du *et al.*, 2001; Xiang *et al.*, 2002). Suspended sediment load in the Yangtze River channel accounts for about 96% of the total Yangtze sediment flux. Annual suspended sediment concentration also has a tendency to decrease from Yichang to Hukou, especially after the flow diversion by Dongting Lake. The mean annual SSC at Yichang is 1.2 kg/m, but falls to 0.674 kg/m^3 at Luoshan, which is downstream of Dongting Lake. This indicates that Dongting Lake is a sink of the Yangtze sediments.

Table 3.3 Hydrological background of the middle Yangtze River. Note: Chenglingji and Hukou stations in the table are located at the mouth of Dongting Lake and Poyang Lake, respectively (adopted from Tang and Xiong, 1998).

Station	Annual runoff (× $10^9 m^3$)	Annual sediment load (× 10^6 ton)	Annual SSC (kg/m^3)	Time period
Yichang	439	526	1.2	1950-1986
Jianli	331	349	1.06	1975-1981
Chenglingji	299	488	0.163	1955-1981
Luoshan	641	432	0.674	1954-1981
Hankou	701	431	0.613	1954-1981
Hukou	146	10.8	-	1950-1981

Yin and Li (2001) attributed the high flood level in the middle Yangtze River to the siltation on valley flat, because the flood not only covers the riverbed, but also the valley flat, silting up of the flat may counterbalance any undercutting of the riverbed temporarily and regionally. They found that the silting rates of valley flats along Jinjiang and around the city of Wuhan have been proved to be quite high (Table 3.4). In a long-term and larger perspective these may prove to be harmful because siltation on the flat will eventually reduce the discharge capacity of river channel.

Table 3.4 Silting up of valley flat along the middle Yangtze River (cited from Yin and Li ,2001).

Locality	Period	Rate of silting(mm/year)
Upper Jingjiang	1965-1995	36
Lower Jingjiang	1952-1976	60
Bank ouside Reming Dayuan	1956-1976	36
Jinzhou-Haoxue,Jianli	1998 flood	656
Huashan(Wuhan)	1998 flood	370
Hankou(Wuhan)	1954-1997	260-340

3.2.2 The Jingjiang reach

The Jingjiang reach has a smaller annual discharge than the upper reach as a result of the diversion of lakes and reservoirs in the basin. Similarly, vast amounts of sediments deposited into the meanders and lakes induced smaller annual sediment load at Jianli station than at the upper-stream Yichang and Xinchang stations (Table 3.5).

Table 3.5 Hydrological characteristics along the Jingjiang reach (Source: Tang and Xiong, 1998)

Station	**Annual discharge (m^3/s)**	**Annual runoff ($\times 10^8 m^3$)**	**Annual sediment load($\times$ 10^8 t)**	**SSC (kg/m^3)**	**Period**
Xinchang	12450	3870	4.65	1.19	1955-1981
Jianli	9590	3310	3.49	1.06	1975-1981

According to Chen and Feng (1999), the river reach from Yichang to Chenjiawan received 0.5×10^8 m^3 of sediments during 1957-1970, but 0.8×10^8 m^3 was washed out as a result of cutoff events downstream and sediment dredging for construction. This reach continued to lose another 0.8×10^8 m^3 from 1981 to 1986 because of the implement of Gezhouba Dam and 1981 flood event (Chen and Feng, 1999). The quasi-equilibrium in this reach was retrieved until the middle of 1980s when the impact of human activities on this reach was ameliorated (Pan and Lu, 1997).

The section from Chenjiawan to Chenglingji suffered more severe erosion after the cutoff events. From 1957 to 1966, 0.7×10^8 m^3 of sediment was washed out in this section, while the volume of washout climbed to 7.5×10^8 m^3 from 1966 to 1987 (Chen and Feng, 2004). Basically the upper Jingjiang reach endured siltation while erosion occurred in the lower Jingjiang reach. Severe siltation in upper Jingjiang reach has made it a “hanging river”. The riverbed of the upper Jingjiang reach is 1-2 m higher than its surroundings, especially in the north bank. During floods, the water level is 6-13 m above the adjacent land. The elevation of areas along the Yangtze River is higher than that of the hinterland because of the siltation within the levees (Wang, 1993). In the lower Jingjiang reach, the embankment and polder near the meanders has blocked the flood diversion and promoted the development of meanders (Wu, 2003). From 1954 to 1965, river channel along the lower Jingjiang reach has widened about 113 m (JLAC, 1991).

3.3 Flood events in Yangtze basin

3.3.1 Causes of flood

The Yangtze basin is located at the meeting point of the Indian and the Pacific monsoons, which makes the rainfall exceptionally difficult to forecast (Varis and Vakkilainen, 2001). The Yangtze basin thereby often encounters floods in the monsoon season. 70% of annual rainfall concentrated from May to October, and is corresponding with floods in the year (Tang and Xiong, 1998). In ordinary years, the rainstorm starts at Poyang Lake and Dongting Lake from April to July. Afterwards, the rainstorm shifts to the north bank and the upstream of the Yangtze River. Upstream of the Yangtze River has rainstorm from July to September, rainstorm occurs from July to October in Han River. Staggered flood time in different parts of Yangtze River and the impoundment of lakes avoid many flood disasters (Liu and Wang, 1999). But when weather is abnormal, floods in middle stream will meet with flood from upstream, and form large-scale flood disasters (Zhang *et al*., 2000).

Basically, there are two types of flood in the Yangtze drainage basin. The first is caused by full area widespread rainstorm in the rainy seasons. Floods in the trunk stream and tributaries of upper reach encounter with flood in the middle and lower reaches, forming high flood peaks, especially large discharge, long duration huge flood (Shi *et al*., 1985). Examples are the floods of 1931, 1954, and 1998. Another is the kind of special high peak and large discharge flood formed by the regional high-density, short-duration rainfall in the same place of the trunk stream and some large tributaries. Examples are floods of 1935, 1981, 1995 and 1996 (Shi *et al*, 1985; Chen, 1999). These floods bring the terrible menace to the plain of middle and lower reaches of Yangtze River, especially to the Jingjiang reach.

3.3.2 Frequency of floods

One of the empirical reasons for intense flood occurrence in the middle Yangtze River is that the outflow from the upper Yangtze River is larger than the channel capacity of the Jingjiang reach. Including the diversion of Dongting Lake, The Jingjiang reach can discharge 60,000 m^3/s water safely. The flood volume at Yichang Station, however, has surpassed 60,000 m^3/s 24 times in the past 100 years (JFPH, 1996).

Floods are regular visitors in the middle and lower reaches of the Yangtze River and floods have occurred ever more frequently in the Yangtze River in recent years. For example, 214 flood disasters were recorded from the Tang Dynasty to the late Qing Dynasty (618–1911) (Yin and Li, 2001). The average frequency during the 1930s and 1940s was once every 5 years, once every 2.5 years from the 1950s to the 1980s, and once every 2 years since 1980, Floods occurred in 1980, 1982, 1983, 1989, 1993, 1995, 1996, 1998, and 1999 (Chen, 1999; Wang *et al*., 2003 Yin and Li, 2001). Zhang *et al.* (2001) stated that the frequency of floods in Dongting Lake of the middle Yangtze River increased greatly. For instance, there was a big flood in the Dongting area every 20 years from 1525 to 1851. Dongting Lake suffered a big flood every 5 years in the following 100 years after 1851. After 1949, the flood frequency was reduced to once every 3.5 years.

Besides the increasing of flood frequency, one of the interesting findings in the middle Yangtze River is the change of flood stage in two major Yangtze floods in the last 50 years.

3.3.3 Typical flood events

Floods originating in the upper reaches usually would not cause serious floods in the middle and lower reaches only if they happen to meet with the simultaneous floods in the downstream (Chen, 1999). For example, in 1981, heavy storms stroke three large tributaries of Yangtze (Min Jiang, Tuo Jiang, Jialing Jiang) in Sichuan Basin (See Figure 3.1) from late June to Mid-September, and brought about a record-breaking discharge of 86,500 m^3/l at Chongqin city. But without rain in other tributaries and downstream, the large discharge from Sichuan gradually decreased downstream 72,000m^3/s at Yichang station in the upper basin and slightly over 45,000 m^3/s at Datong station in the lower basin. Therefore, the flood in the upper reach did not affect the lower reach of Yangtze River in 1981 (Shi *et al*, 1985).

The basin-wide flood as a result of simultaneous storm season in both upper reach and middle reach produced the massive flood damages. Floods in 1954 and 1998 are two of these most disastrous floods occurred in the Yangtze Basin. In 1954, rainstorms happened in the middle stream and water system of two lakes (Dongting Lake and Poyang Lake) from June to July and extended to August. On August 2, outlet peak discharge from Dongting Lake reached 44,500 m^3/s at Chenglinji. Flood peak discharge at Yichang reached 66800 m3/s on August 7, which caused great flood damages (Zhang *et al.*, 2000).

Table 3.6 Comparison of 1954 flood and 1998 flood on Maximum water stage and Maximum discharge (adopted after Xia et al., 2001).

Station	1998 floods		1954 floods		Duration over the warning stage(days)		
	H_{max}(m)	Q_{max}(m^3/s)	H_{max}(m)	Q_{max}(m^3/s)	$H_{warning}$(m)	1998 floods	1954 floods
Yichang	54.5	63,300	55.73	66,800	52	44	38
Zhichen	50.62	68,800	50.61	71,900	49	31	19
Shashi	45.22	53,700	44.67	50,000	43	57	34
Jianli	38.31	46,300	36.57	36,500	34.5	82	64
Luoshan	34.95	67,800	33.17	78,800	31.5	81	72
Wuhan	29.43	71,100	29.73	76,100	26.3	84	100
Jiujiang	23.03	73,100	22.08	73,000	19.5	94	116
Datong	16.32	82,300	16.64	92,600	14.5	83	107

Similarly, in the 1998 flood, floodwater from the upper reaches exacerbated the flooding in the middle and lower reaches. Flooding in 1998 along the upper and middle reaches of the Yangtze River began in middle June and extended into early August. El-Nino and other factors caused 74 days of storm in the Yangtze River basin (Chen, 1999). It was recorded that the 1998 flood had a higher flood level but smaller flow volume than in 1954. The flood duration over the warning water stage was longer than it had been in the 1954 flood (Yin and Li, 2001； Table 3.6).

After comparing the flood level in the 1954 and 1998 floods, He (2000) found out the gauging stations along the Jingjiang Reach had a higher flood stage in the 1998 flood than it was in the 1954 flood, although flood discharge in 1998 was not greater than it in 1954. This finding was commonly regarded as an evidence of siltation in the middle Yangtze River, and was supported with the analysis on the basis of hydrological data. According to YWCC (2000), about $4\times10^8\,m^3$ sediment was washed out of the channel in the Jiangjiang Reach, mainly in the upper Jiangjiang Reach. Basically, erosion and deposition co-exist in the lower Jiangjiang Reach due to the high sinuosity. Below this meandering lower Jiangjiang Reach is the braided reach from Chenglingji to Wuhan, which has silted up $2.5\times10^8\,m^3$ sediment. Without examining river channel itself, Yin and Li (2001) presumed that the worsening flood risk in the middle Yangtze River could be attribute to the extensive human activities like vegetation destruction, lake reclamation and levee construction in the river basin.

3.3.4 Flood damages

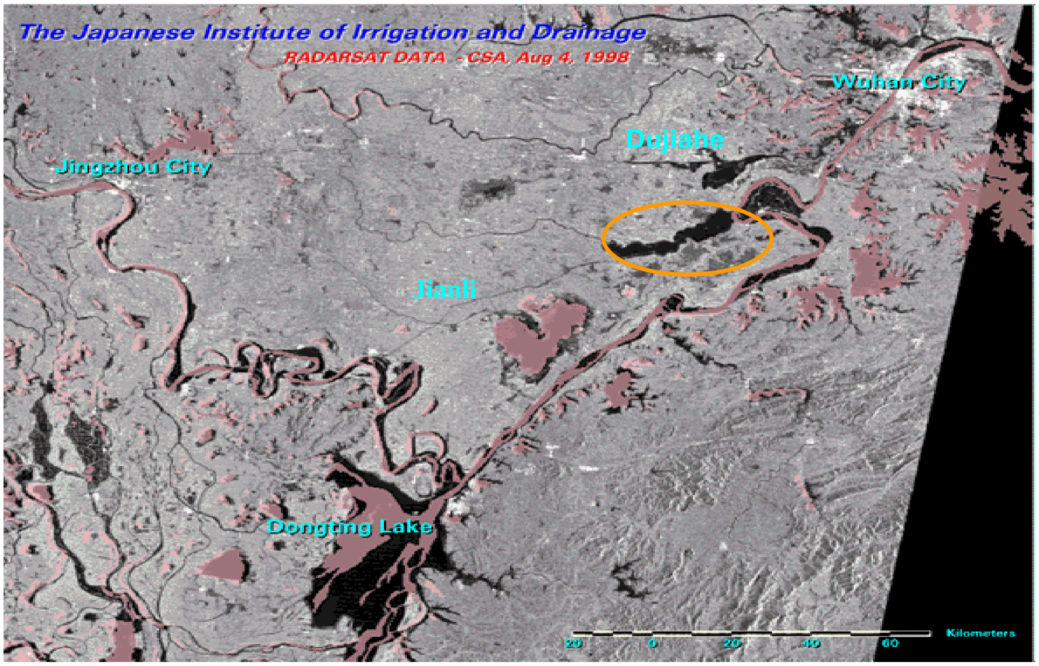
In fact, flood represents the most serious natural disaster in the Yangtze basin. When large floods occur, they cause tremendous damage to human structures in the floodplains of the middle and lower reaches of the Yangtze basin. Floods claimed at least 200 lives in every flood season from 1952 to 1989, and in 1961, 1981 and 1989, killed more than 1,000 people and damaged large areas of farmland (Chen, 1999). It is worth noting that the economic development in the floodplain increased the flood damage and loss. For instance, six flood events occurred from 1990 to 2000 have caused much greater economic and social losses than the total loss during the floods from 1931 to 1990 (Li *et* *al.*, 2000). Table3.8 lists the most serious floods recorded in the 20th century. Under the control of all kinds of levees along the banks, the death toll is less in the latest flood events, but the economic loss has mounted to 1070 $\times 10^8$ Yuan and the population affected reaches 7114$\times 10^4$ in the 1998 flood, due to the extensive land use in the flood prone area (Table 3.7).

Table 3.7 The most serious flood damage in the Yangtze River (Adopted Wang et al., 2003).

Year	Type	Peak discharge (m^3/s)		Inundated land ($x10^4$ ha)	Population affected ($x10^4$)	Population loss (person)	Economic loss ($x10^8$ yuan)
		Yichang	Hankou				
1931	The whole region	64600	59900	339.3	2850	145000	13.45
1935	The middle and lower reaches	56900	59300	150.9	1003	142000	3.55
1954	The whole region	66800	76100	317	1888	33169	100
1981	The upper reach	70800	52900	117.1	2000	1358	25
1991	The middle and lower reaches	50400	65700	291.2	3199	514	218
1996	The middle reaches	42400	70300	486.7	7000	800	700
1998	The whole region	63600	72300	460	7114	1464	1070

Among these flood events, the flood in 1954 and 1998 particularly drew attention from research scholars because of the great losses they caused. During the 1954 flood, the storm lingered in the whole Yangtze Basin from May to July and caused a disastrous centurial flood. According to YWCC, 3.17 km^2 farmland and 18.88 million people were affected in this flood, 33,000 people were killed and 427.6 houses were damaged (YWCC, 1999; Table 3.7).

Figure 3.3 On-propose levee breaches and inundation in the 1998 flood.



The 1998 flood affected the provinces of Anhui, Zhejiang, Jiangxi, Jiangsu, Hubei, Hunan, Chongqing, Sichuan and Guizhou. This flood damaged 2,128,000 houses and killed about 1500 people (YWCC, 1999). The estimated economic loss from the flood of autumn 1998 was about 166 billion Yuan (about 20 billion US dollar) (Chen *et al.*, 2001a). Flood diversion into the flood retention area in 1998 has minimized the damage of this extraordinary flood. For example, in order to ensure the security of Wuhan City, the levee at the Dujiahe polder upper stream of Wuhan was deliberately breached to divert the flood (Figure 3.3).

3.4 Human activities

Intense flood disasters in the middle Yangtze River drew attention from Chinese hydrologists and geomorphologists (Yin and Li, 2001; Yang *et al.*, 2002; Yin, 2004). The more and more frequent floods make people reflect on the human interventions in the natural environment (Du *et al.*, 2001; Xiang *et al.*, 2002; Lu and Zheng, 2004).

3.4.1 Impoundment construction

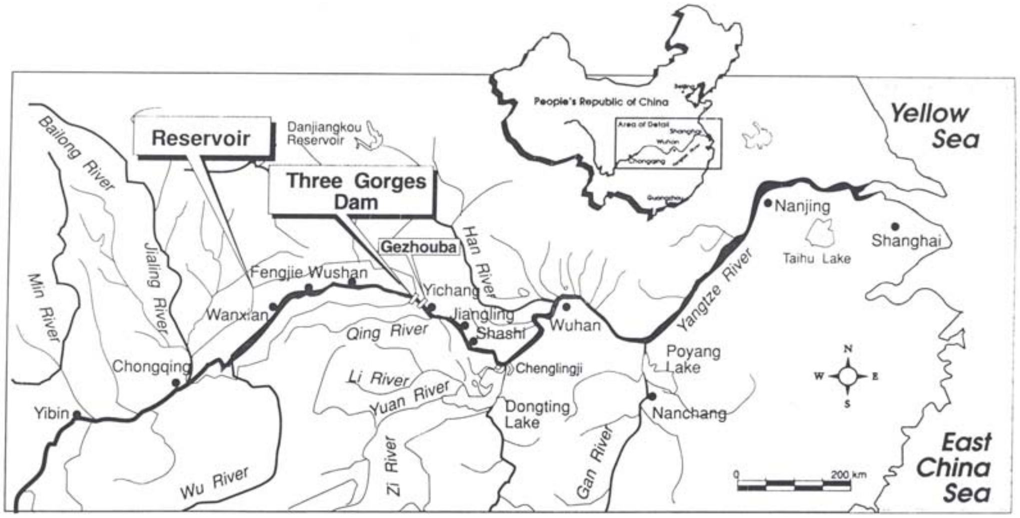
Reservoirs are important measures in preventing floods in the Yangtze River as they can adjust the water discharge in flood and drought seasons. Dams have been constructed in the Yangtze River basin since the founding of P.R. China. 83,387 dams and reservoirs had been built in China from 1949 to 1990 (Fu, 1998). According to Wu (2003), over 40 thousands reservoirs have been constructed in the Yangtze River basin, 119.5 billion m^3 in total capacity. It was estimated by Yang *et al.* (2001) that the amount of sediment retained by the reservoirs in the upper Yangtze basin increased from 5×10^6 to 100×10^6 tons/year from 1950 to the middle 1980's, and amounted to 230×10^6 tons/year in 1990. Sedimentation in reservoirs and lakes caused the reduction of sediment supply downstream (Table3.9). Meanwhile, sediment deposition in 230 of these reserviors has resulted in a combined loss of 14% of the total storage capacity (Leopold, 1996).

Table 3.8 Sedimentation in the reservoirs in the Yangtze basin (adopted after Luk and Whitney,1994).

Type	Number	Capacity(10^6m^3)	Sedimentation(10^6m^3)	Lost capacity(%)
Large reserviors	23	25638	1293	5.04
Medium reserviors	12	257.55	24.18	9.09
Small reserviors	182	92.34	19.78	21.42
Ponds	6492	74.24	41.48	55.9
Total	6709	26062.13	1378.44	5.29

Among the numerous reservoirs in the Yangtze basin, the ongoing TGP is the largest one as it was claimed to fulfil one-tenth of the country's electricity needs and was designed to improve flood prevention along the Yangtze River. The dam is sited at Sandouping, Xiling Gorges, 47 km upstream of Yichang (Figure 3.4). This dam will control a drainage area of about one million km^2, about 56% of the Yangtze drainage basin. The annual flow at the dam site is 450 billion m^3, about half of the Yangtze runoff which is 960 billion m^3 (Hong, 1993). This huge project will submerge vast tracts of farmland and relocate 1,200,000 people and destroy many 1000-year old culture relics and antiquities such as Zigui, Shibaozai, Fengdu (Fang and Wang, 1993). Permanent and temporary inundation affects nineteen counties and cities, which have a total population of 13 million and an administrative territory extending more than 50,000 km^2 (Tian and Lin, 1993).

Figure 3.4 The location of Three Gorges Dam (Adopted from Fu, 1998).



3.4.2 Cutoff events

Several major meander cutoffs on the lower Jingjiang reach occurred in the 1960s and the 1970s to facilitate the flood conveyance and navigation (Pan, 2001):

1) Zhongzhouzi Cutoff project started in October of 1966 at the 37 km long Zhongzhouzi bend. The new cannel was 4.3 km. The radius of the meander was 2.3 km. The ratio between the length of pre-meander and the length of new channel after cutoff events is 8.5 (YWCC, 2000). The project was completed in May 1967, and the new channel became the major navigation channel in the winter of 1967. The revetment of the new cannel was carried out from 1968 to 1971 (YWCC, 2000). The bed of the new channel is covered by 6 meters of silt in the upper layer and fine sand in the lower layer. The area of the cross-section was 1/30 of the previous one.
2) In 1968, another cutoff project was carried out at Shangchewan bend, which was 33 km in length and the shortest distance between two limbs was 3 km. The new channel is 3.75 km and the cutoff ratio (the ratio between the length of pre-meander and the length of new cannel) is 9.3. The radius of the meander was 2 km. 20 to 30m of silt and fine sand constitute the riverbed of the new channel, of which the cross-section area was only 1/25 – 1/17 of previous bend. The new channel became the main navigation channel in 1971 (YWCC, 1955-1974).
3) Shatanzi meander was 37 km downstream of Ouchikou. The shortest distance between two limbs was 1.5 km in 1970. The natural Shantanzi cutoff occurred in July 1972 before the proposed date of artificial cutoff (YWCC, 2000; Lu and Zheng, 2004).

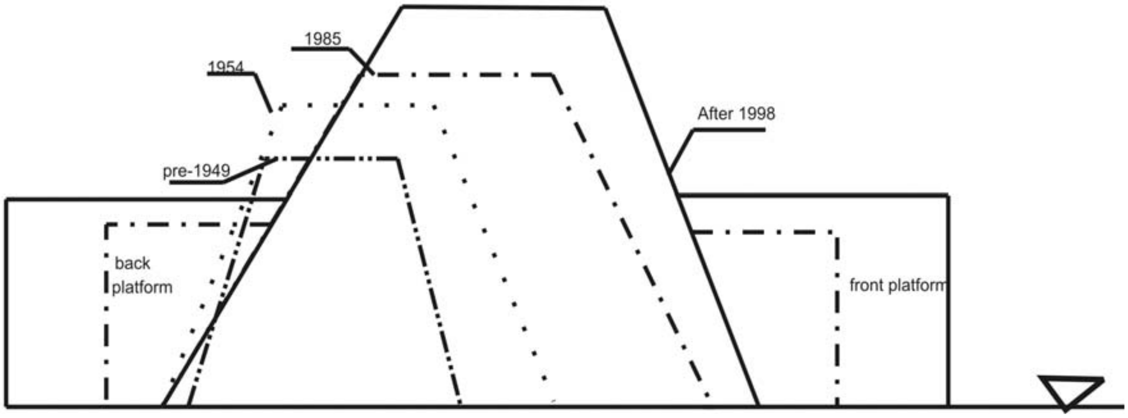
Some examined the impact of three aritficial cutoffs in the lower Jingjiang Reach. These three cutoff events in the Lower Jingjiang reach have shortened the channel length by 78 km, which eases navigation. The shortened Yangtze River deteriorated bank erosion and river degradation along the river. Lu and Luo (1997) suggested that artificial cutoff projects and Gezhouba dam construction contributed to the reducing of water level from Yichang station in the upper reach to Chenglingji station in the middle reach of the Yangtze River. At the same discharge volume, the water stage at Shashi, Xinchang and Shishou decreased 0.5 m, 0.65 m and 1.05 m respectively (JLAC, 1991). Similarly, at the same water stage, the volume of discharge at these stations increased, thereby released the diversion burden of Dongting Lake and facilitated the flood prevention in Jingjiang and Dongting area (Duan, 1994). Lu and Zheng (2004) indicated that 4 shoals in the channel eliminated because waterway length was shortened after cutoffs. However, Pan et al. (1997) the effect of cutoff events in the lower Jingjiang Reach faded away until the 1980s based on the analysis of the flow regime in the channel.

3.4.3 Levee construction

River embankments in China are characterized by homogeneous earth with high permeability and seepage. Levees along the Yangtze River are not an exception. The levees along the Jingjiang reach were based on the Quaternary sediments with 2-7 meter upper fluvial silt layer and a basal sand layer. Most of them consist of upper layers with low permeability and lower layers with over 50 m of high permeability. The lower permeable layer directly comes under river water pressure, therefore making soil seepage control very difficult (Liu *et al.*, 1998). Given its long history and weak foundation, levees along the Jingjiang reach have to face three problems: infiltration in the levee body, scouring at the toe of levee and bank collapse. Once there is a levee breach, the death toll could reach 100,000 or more. Moreover, the security of Wuhan city, which has 8 million people and 18,000 km^2 arable land, would be threatened (Hong, 1993).

The earliest levee along the Yangtze River is the Great Jingjiang Levee, which was funded by local government or local residents in flood affected region 1600 years ago. The Great Jingjiang Levee was made of sand and gravel, with a very thin silt layer on the top. Without sufficient money and human power, historical levees were erected by connecting the scattered embankments nearby the banks. Till 1926, the state government started to allocate funds on levee construction along the Yangtze River. Since then the Changjiang major levees, together with the Great Jingjiang Levee were listed as one official project supported by Chinese central government. The Changjiang major levee was 8 meters above the earth surface it stood, and 4 meter in width on the top of the levee in 1949, there were a few settlements on the slope and top of the levee. From 1949 to 1954, Chinese government reinforced Changjiang major levees (including the Great Jingjiang levee and the Changjiang levee) to 1 meter higher than 1949 flood stage and 6 meter in width. During the 1954 flood (the largest flood since 1949), the peak flood stage was above the warning flood stage for about 69 days at Jianli station (JLAC, 1991). After 1954, new criterion of levee along the middle Yangtze River was put forward to prevent similar flood event. The levee along the Jianli sub-reach was strengthened with another 0.5 meter above 1954 flood stage and 1 meter wider in the top of levee in 1969 (JLAC, 1991). With more funds allocated from Chinese government, a comprehensive reinforcement on levees in the Yangtze basin has been done in the past 40 years. Not only the height and width of levee body was strengthened, platforms of 30-50 m wide, 7-8 m thick were also raised up in front of and behind of the levee in 1985 to reduce the saturation and seepage in levee during flood season (JLAC, 1991). After the disastrous flood in 1998, 28.2 billion RMB was allocated on the Changjiang levee to enhance the ability of defence flood (XNA, 2003; Li *et al*., 2001). Therefore, the levee along the Middle Yangtze River was further reinforced to 10-12 m in width, and 1.5-1.7 m higher than before (Figure 3.5). The platforms also strengthened to 50 m wide for front platform, 30 m wide for back platform and 6-7 m below the top of levee (Li *et al*., 2001). Today there stand 30,000 km levees, including the 184.2 km Jingjiang Levee and 3800 km Yangtze major levee in the middle and lower Yangtze reaches (Wu, 2003).

Figure 3.5 Sketch of levee along the middle Yangtze River. The front platform faces to the river flow. New levees were reinforced on the base of the old ones, thus the front of the levee migrated to the river channel in order to prevent higher flood.



The Jingjiang flood diversion area consists of the Jingjiang detention area, Yuanshi extention and Huxi diversion and Renmin Dayuan (polder behind the levees). The flood diversion area is 1358 km^2 and can withstand 7.16×10^8 m^3 of floodwater. The flood diversion areas are linked to 94.3% of the whole Jingjiang Levee (JFPH, 1996). These areas are very vulnerable to flooding and carry the burden of retaining floodwater to protect densely populated cities such as Wuhan City with over eight million population. During 1998 flood, the levee around “Sanzhoulianyuan” was deliberately opened to assure the safety of Wuhan city and Jianghan fluvial plain.

Plate 1   Yangtze major levee at Jianli County before 1998.

Plate 2   Jianli Levee in big flood event.

Plate 3   Yangtze major levee at Jianli County after 1998.

The levee-protected Jingjiang section can withstand a flow less than 60,000 m^3. With flood diversion, a flood discharge of 70,000 m^3/s can be withstood, but 3,100,000 people and 710 km^2 of flood diversion area would be affected in this case (Luk And Whitney, 1993). Pre-1998 Jingjiang levee condition with diversion can only prevent 10 to 20 year flood. After the 1998 flood, the Jingjiang Levee was reinforced to have the warning stage at 45 m in Shashi and 34m at Chenglingji, respectively. The height of levee is 2 m higher than the warning stage (Li *et al.*, 2001). This measurement was very effective in flood prevention during major flood events in 1999 and 2002. Water levels in the 1999 flood came close to the record levels in 1998 flood, but overall the flooding caused much less damage and was about a month less in duration (Wu, 1999). Similarly, the floodwater exceeded the previous danger levels twice in 2002 for nearly a month without a major danger risk (XNA, 2003). The water level of the Yangtze in the summer of 2002 almost equalled that of 1998, but no disaster occurred thanks to the solid new embankments (Zhao and Liao, 2001).

Scholars have predicted the impact of implement the TGP on Jingjiang levee and river channel. Regulation of peak flow by the TGP lowers the water level in the Jiangjiang Reach, which is favorable for flood prevention, but the sediment trap behind TGD may induce the scouring at the base of the levees along the Jingjiang reach and consequently cause levee failures (Fang, 1993).

3.5 Conclusion

It is noticed that most of the aforementioned studies chose hydrological data from YWCC rather than on-site observation survey to examine the sediment transport and the flood occurrence dynamics in the Yangtze River (Chen *et al.*, 2001; Yin and Li, 2001; Rey, 2003). This may be due to the great expense and difficulties in the cooperation of the field survey in the large Yangtze River. However, these hydrological data cannot directly represent the topography changes in the river channel, as they can't provide the 3D image of the river channel.

Only a few managed to reconstruct the historical channel to examine the changes in the channel with historical map sources. Zhang *et al.* (2001) have tried to simulate the channel change in the Zhengyang reach in lower Yangtze River. DEMs based on the 1:10,000 bathymetric maps in 1983, 1987, 1990, 1994 and 1998 demonstrated the erosion trend in the reach during this period. Yan *et al.* (2001) predicted the tendency of channel evolution in the lower Jingjiang Reach by comparing the sinuosity of the lower Jingjiang reach calculated from historical river course maps in different years. But, their studies either don’t cover the most severe flood-affected reach, the Jingjiang reach, or illustrate the topography changes in the riverbed. Moreover, the distribution of erosion/deposition area in the middle Yangtze River is still unknown. Thus, a holistic study on the river channel geometry change in the lower Jiangjiang reach, the most meandering and flood-triggered reach is of need.

Chapter 4. DATASET AND METHODS

As the most meandering reach along the Yangtze River and an area subject to severe flooding, the Jianli sub-reach was selected in this study, to investigate channel changes in response to human intervention and floods in the past five decades. On-site cross-section survey data (pre-1987) and map materials (1951-1997) were employed in the study.

4.1 Datasets

To solve the problem of discontinuous data records, this study uses two data series. One is historical hydrological survey data (1954-1987), the other is map materials. Hydrological data involved in the study include statistics on water discharge, sediment load, water level and cross-section observational data (1954-1987). Map sources used in this study are:

1) River channel evolution map (1:100,000 in 1951, 1965 and 1974)
2) Navigation charts (1:25,000 in 1981 and 1997).

As the cross-section data derived from hydrological survey (1954-1987) are not consecutive for every cross-section, navigation charts (1:25000) in 1981 and 1997 are used for DEM construction and extracting cross-sections along the study reach. Cross-section profiles derived from two kinds of dataset should be compared and combined for better understanding of the channel changes in the study area.

4.2 Analysis on the basis of hydrologic survey data

4.2.1 Water discharge and sediment load

Water and sediment discharge data along the study area were extracted from Yangtze Hydrological Yearbook. Changes in the water and sediment regime are key to understand the reason of channel change. The results of this analysis will be used to gain a better understanding of channel change in the study reach.

4.2.2 Cross-section changes

First, five cross-sections at the major stations (Yichang, Xinchang, Jianli, Luoshan and Hankou) were used to examine the changes along the Middle Yangtze River. Then observational data of 15 cross-sections along the Jianli sub-reach from 1954 to 1982 was collected to examine the channel geometry change. These cross-section data were derived from regular surveys (>2 times/year) on the Yangtze River conducted by theYangtze Water Conservancy Committee (YWCC). Special attention was paid to examine the impact of artificial cut-off events, and large flood events like the 1954 flood and 1981 flood.

4.3 Analysis on map materials

4.3.1 Historical maps

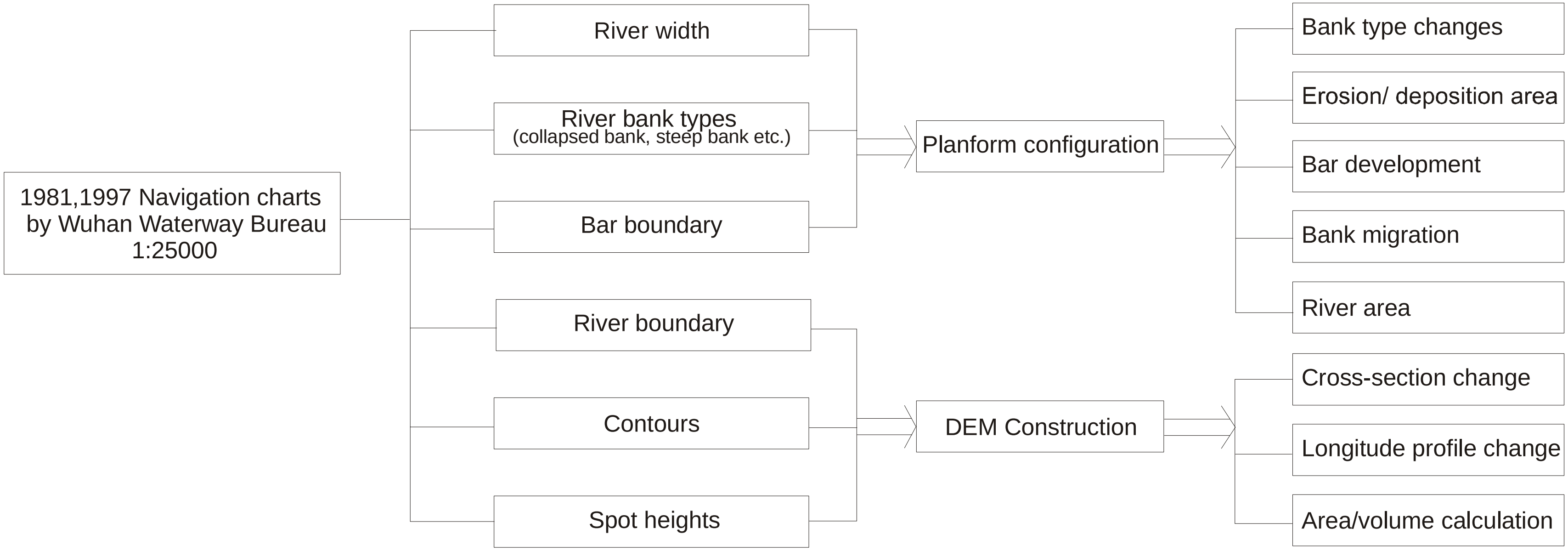
Historical maps can provide much information on large rivers including considerable details of river channel changes (Hooke and Redmond, 1989; Braga and Gervasoni, 1989; Pišút, 2002). Channel distribution maps (in 1951, 1965 and 1975) of the Jianli sub-reach were collected to identify bank shifting in the study reach during this 25 years period. These historical maps are still a very good evidence to represent the evolution of channel and human impact. As these are small-scale maps (1:100,000) without any contours of riverbed, DEMs cannot be built up on the basis of these maps.

Different from channel evolution maps, navigation charts contain more detailed information such as elevation, bank type (Figure 4.1), and the scale (1:25,000) are suitable for DEM construction in such a big river. It should be noticed that, for comparative and consecutive study in channel migration, all the 1:25,000 navigation charts were converted into 1:100,000 maps to match with channel distribution maps.

4.3.2 Construction of DEM

As DEM represents landform surface variability well and provides the opportunity to measure and monitor morphological change, it has become a very popular method to study the channel geometry and geomorphology. In this study, building up DEM for the study reach is a good approach to acquire the profiles of transactions and riverbed after

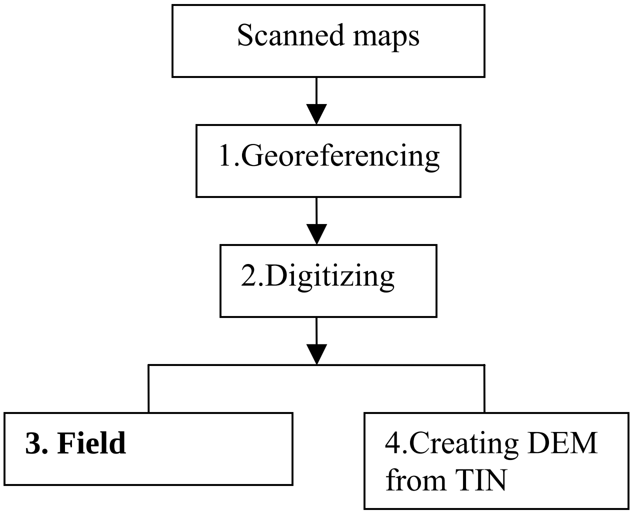
Figure 4.1 The parameters derived from navigation charts.



1987. It helps to calculate the volume of erosion and deposition in the channel. Still rather few DEMs based on navigation charts were set up along the Yangtze River to discuss the channel change and its effect on floods (Yan *et al*, 2001). Building up DEM involves four steps (see flowchart 2):

1) Georeferencing,
2) Digitizing,
3) Field calculation and
4) Creating DEM from TIN.

Figure 4.2 The process of DEM construction



1. Georeferencing

For this study, large scale (1:25,000) navigation charts of the Jianli sub-reach in 1981 and 1997, with spot heights and contours in river course, were collected from the Wuhan Waterway Bureau. The channel distribution map (1:100,000) from the Yangtze

Hydrological Yearbook was used for identifying bank migration. These charts and maps were scanned and imported into ArcMap^{TM} 8.3 (ESRI$^{®}$) as raster datasets. All charts and map were drawn under the 1954 Beijing coordinate system. In order to represent the real-world location of the Jianli sub-reach and promote quantitative calculation about changes in the channel, these raster datasets were converted from the 1954 Beijing coordinate system into a real coordinate system. In this study, the Projected Coordinate System is WGS_1984_UTM_Zone_51N, and Geographic Coordinate System is GCS_WGS_1984.

To georeference each raster dataset to a real-world coordinate system, 4-6 control points were selected, whose locations are recognizable in both coordinate systems for each raster. After georeferencing, 6 consecutive navigation charts of each year covering the Jianli sub-reach can overlay with each other in AcrMap.

2. Digitizing

Digitizing is the process of converting images on a printed map into digital format. After scanning and georeferencing all the maps, all the features (see Figure 4.1) from maps and charts have been digitized with the on-screen digitizing function of the editing tools in ArcMap.

Digitized features include river boundaries, contours, spot-heights, different types of levees and banks. Among them, only contours and spot-heights contain elevation information, which can be read from the chart directly. All the elevation values given in the navigation charts are based on a so-called “navigation reference plane”, along which a safety navigation in the Yangtze River is guaranteed. This navigation reference plane is fixed over time. Bathymetric contours under navigation reference plane and contours on islands above navigation were, respectively, marked as negative and positive values. So were the values of spots height in these charts. After tracing all contours and spot-heights with on-screen digitizing, their elevation values were added into their attribute tables.

3. Field calculation

Field calculation, like updating area and length, was made in the attribute table with VBA statements. VBA statements for calculating length/perimeter of polyline and polygon shapfiles are as follows:

```
Dim dblPerimeter as double
Dim pCurve as Icurve
Set pCurve = [shape]
dblPerimeter = pCurve Length
```

Similarly, the area of polygon shapefiles can be calculated with the following VBA statements:

```
Dim dblArea as double
Dim pArea as IArea
Set pArea = [shape]
dblArea = pArea.area
```

With these two VBA scripts, the length of different types of banks and levees, the area of bars and the whole reach can be obtained for channel planform analysis.

4. Creating DEM

Using two shapefiles (containing contours and spot heights) with elevation values in their attribute table, 3D analysis extension in AcrGIS can create TIN (Triangulated Irregular Network) for the Jianli sub-reach in 1981 and 1997. In TIN, a surface representation is derived from irregular spaced points and breakline features. Each sample has an X and Y coordinate and a Z value or surface value. Two DEMs for the Jianli sub-reach in different years were converted from TIN for better data presentation.

The 3D analysis extension is used for doing surface analysis, with which cut/fill area and volume can be estimated. By allocating any interpolated line on TIN or TIN converted raster, profiles for any transaction can be created along study reach.

4.3.3 Channel planform change analysis

Bank shifting and channel width of study reach can be estimated by comparing the 1951, 1965, 1975, 1981 and 1997 river boundaries digitized from historical channel evolution maps and navigation charts. The evolution of bars in the river course from 1951 to 1997 have been computed by comparing the channel area and island area. The river surface area and island areas were calculated with “field calculation” in the attribute table. Twenty transactions with 5 km intervals were allocated along the study reach so the river width of each transaction can be measured.

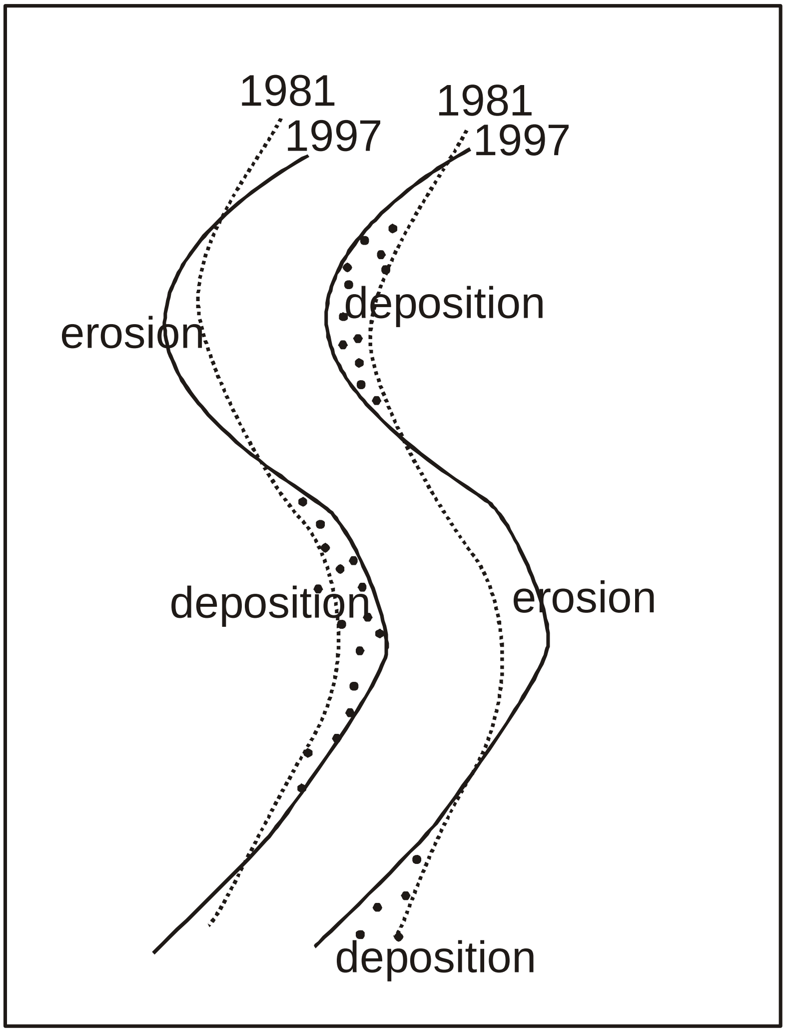
4.3.4 Cross-section change

River cross-sections can reveal irregular riverbed profiles, which are constantly changing with time in response to the processes of erosion and deposition (Abam and Omuso, 2000). Although YWCC has recorded numerous cross-section observational data along the Yangtze River, after 1987 this data was not compiled and published. Luckily, 3D analysis extension in AcrView can help to make up the lack of cross-section observational data after the 1980s. Twenty cross-section profiles along the Jianli sub-reach were extracted with 5 km intervals from 1981 and 1997 DEMs to provide a consecutive temporal trend of cross-section change in the Jianli sub-reach.

4.3.5 Statistics derived from DEMs

One objective of this study is to estimate the area and volume of deposition and erosion in the Jianli sub-reach after 1980. This information is employed to understand the mechanism of intense flood event in the middle Yangtze River. Erosion/deposition area can be obtained by comparing the area of river channel in different years. The river area, which disappeared in later years, is called “deposition area”. While, the river area, which was not within the channel in the earlier years, but appeared in the later channel, is called “erosion area” (see Figure 4.3).

Figure 4.3 **Demonstration of erosion/deposition area**



The Cut/Fill function helps to identify the areas that have been eroded and the areas of deposition related to the “no change” area. It also calculates the volume of surface material that has been cut or filled in each area. By taking two surface rasters of a given area from two different time periods, the Cut/Fill function will produce a raster displaying regions of surface material addition, surface material removal, and areas where the surface has not changed over this time period. Negative volume values indicate areas that have been filled, while positive volume values indicate regions that have been cut (see Figure 4.4).

Figure 4.4 Demonstration of cut/fill area.

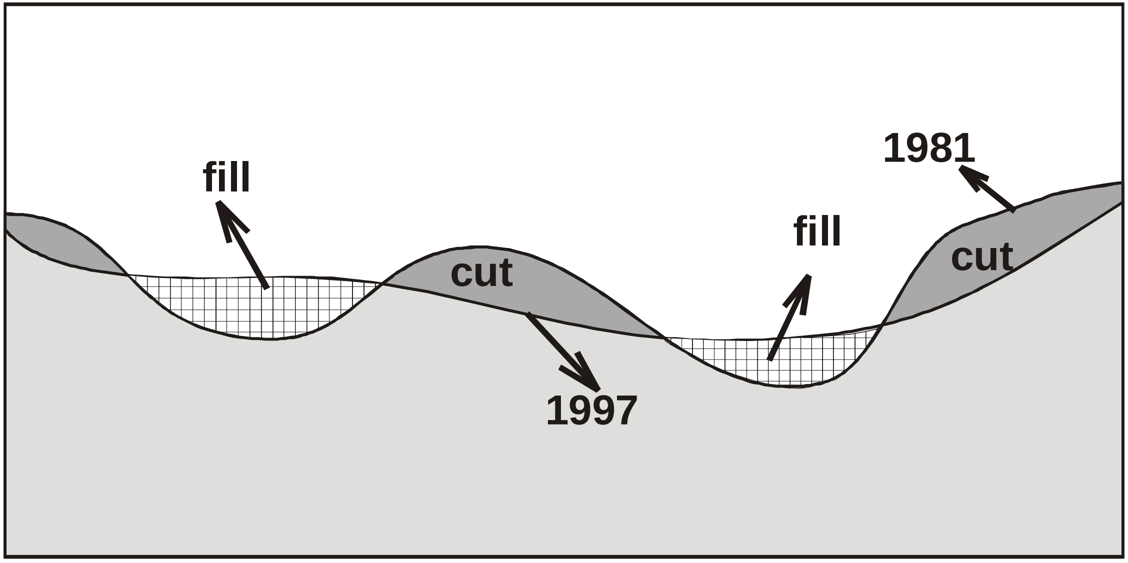
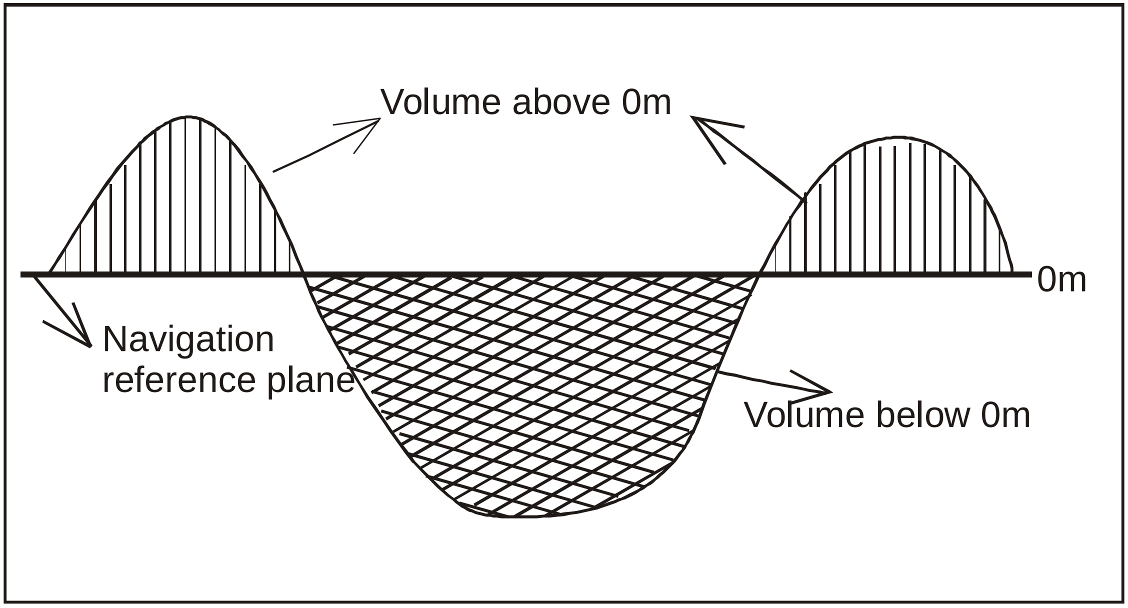


Figure 4.5 Demonstration of erosion/deposition volume



Changes in bed profile can be translated into volumes of eroded or deposited materials by considering a unit horizontal thickness in the cross-section (Abam and Omuso, 2000). The "Area and Volume Statistics" tool in 3D analysis extension was used to calculate 2D area, surface area, and volume. The navigation reference plane was selected as the bench mark for the volume calculation. The volume is the space (in m^3) between the surface and a reference plane set at a particular height. The volume below the bench mark is the in-channel space under the navigation reference plane, while the volume above the bench mark means the volume of flood plain above the navigation reference plane (see Figure 4.5).

As for TIN, the values for the 2D area and surface area indicate the roughness or slope of the surface, the larger the difference between the values, the rougher or steeper the surface. The 2D area of a rectangular patch of surface model is simply its length times its width, while the surface area is measured along the slope of the surface, taking the variation in the height of the surface into account. The 2D area and surface area for each DEM in the Jianli sub-reach were also computed with the "Volume calculation" function in the 3D analysis tool.

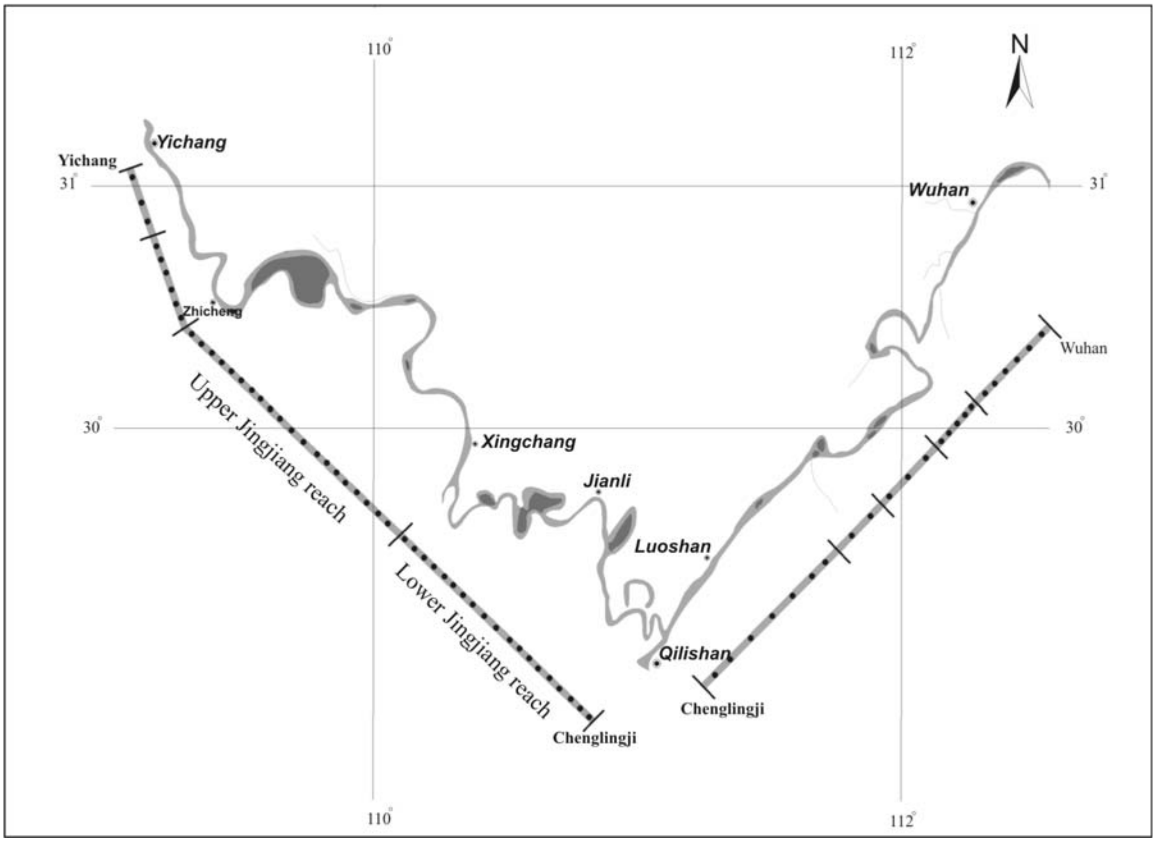
Chapter 5. CROSS-SECTION CHANGES DERIVED FROM HYDROLOGIC SURVEY

5.1 Cross-sections along the middle Yangtze River

Five cross-sections at Yichang, Xinchang, Jianli, Luoshan and Hankou along the middle Yangtze River (Figure 5.1) were examined on the basis of annual hydrologic survey data. The most obvious change at the Yichang cross-section is on the floodplain in the north bank (normal water level here is less than 40m) from 1975 to 1981 (Figure 5.2a).It can be seen in Figure 5.2a that about 15m thick of sediments plumped at the north bank, while the riverbed was subject to erosion in the left part from 1965 to 1987, however the south bank is very stable. This may be attributed to different topography on both banks. The south bank is rock dominant plain with high resistance. The plump on the north bank may be related with levee construction on banks, which rose up the elevation of its north bank.

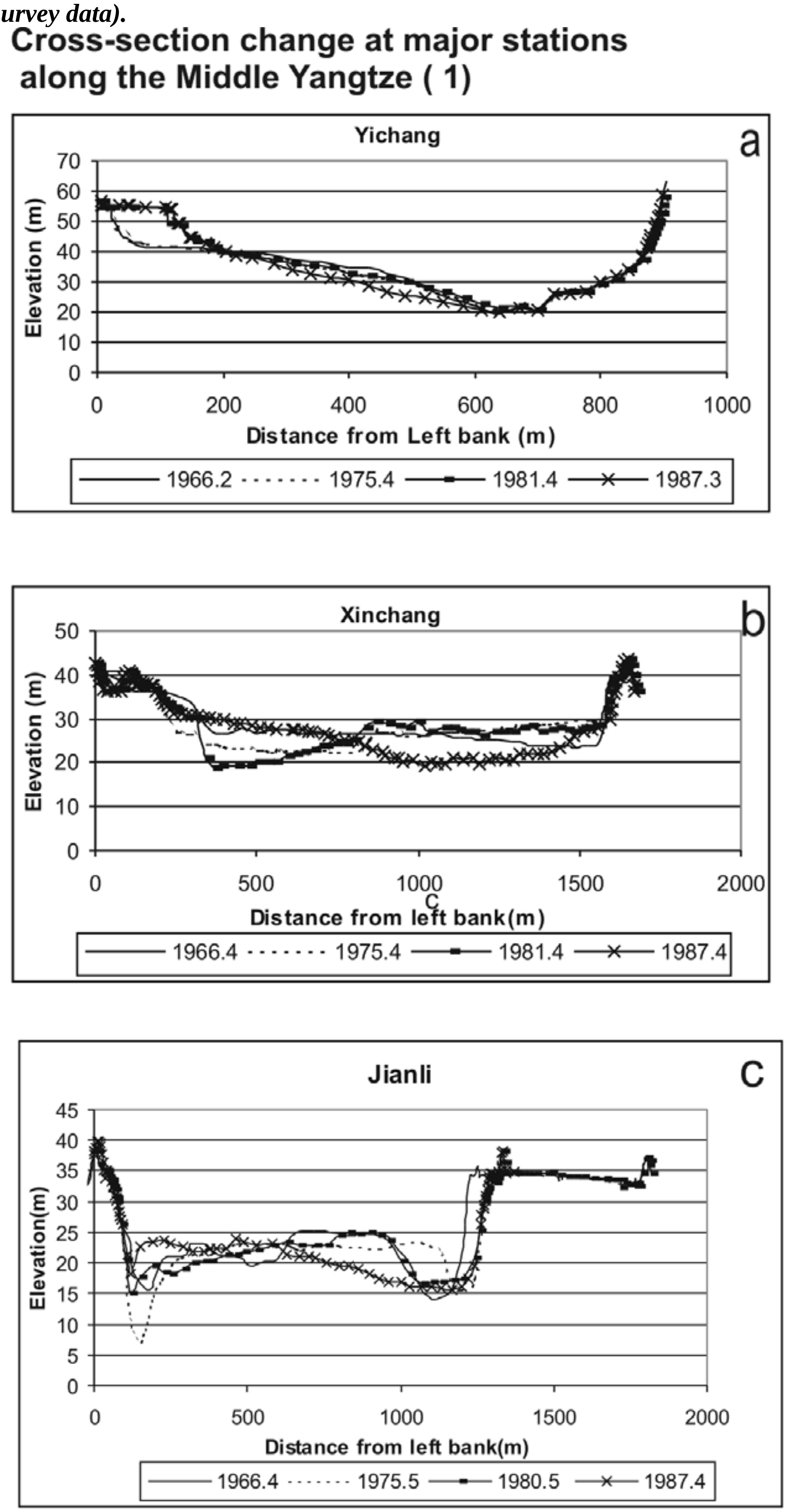
Cross-section at Xingchang is the most varied cross-section along the middle Yangtze River (Figure 5.2b). From 1966 to 1975, the river channel was scoured at north bank, and deposited near south bank. This tendency continues until 1981. However, a completely contrary change in the riverbed occurred from 1981 to 1987. The lower place in the riverbed near north bank was silted up, but the riverbed near south bank was eroded and became the thalweg in this profile.

Figure 5.1 Location of major stations along the middle Yangtze River.

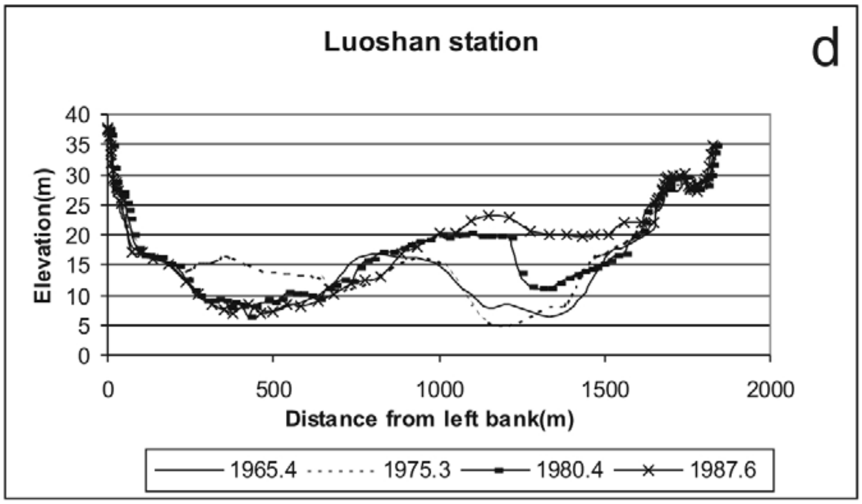


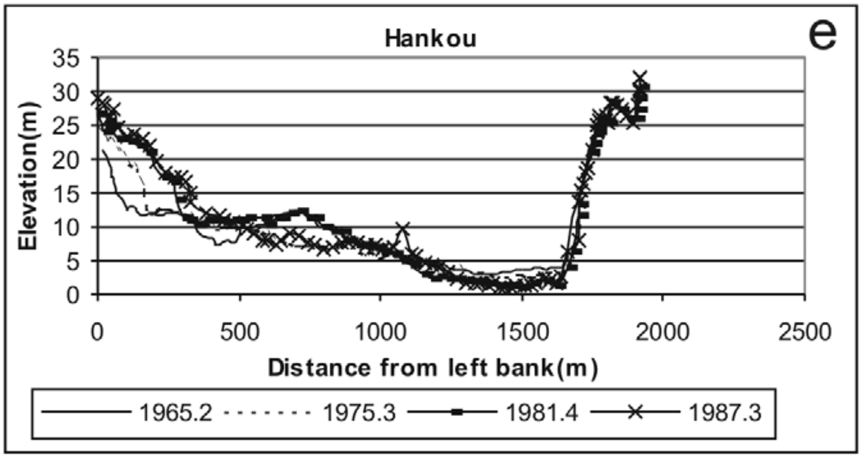
Different from cross-sections at Yichang and Xinchang, which have a "V" shape channel valley with extinct thalweg, cross-section at Jianli has a much flat riverbed, although it has two channels near the toe of both banks (Figure 5.2c). The deepest channel for navigation was near the south bank in 1965, and shifted nearer the north bank in 1975. However, the left channel (north channel) was silted from 1975 to 1980, while the south channel was scoured about another 3 m during the same period (Figure 5.2c). Besides, south bank retreated around 50 m from 1966 to 1975 (Figure 5.2c).

Figure 5.2 *Cross-sections at major stations along the middle Yangtze River (Data source: YWCC Cross-section survey data).*



Cross-section change at major stations along the middle Yangtze (2)





Cross-section at Luoshan looks like an irregular "W" (Figure. 5.2d). The left part of riverbed at Luoshan station received massive sediments from 1965 to 1975, these deposits (about 10 m in depth) were again removed from 1975 to 1981, meanwhile sedimentation happened on the opposite part, about 12 m of deposits was silted in the right channel from 1975 to 1981 (Figure 5.2d).

Hankou station has a "V" type cross-section (Figure 5.2e), alike the cross-section at Yichang. Basically, this channel is quiet stable, especially at the right side. Siltation mainly occurs at the north bank, north bank moved inward gradually from 1965 to 1987.

5.2 Cross-sections along the Jianli sub-reach

Results in the former section indicate that the meandering lower Jingjiang reach has the most various cross-sections. Therefore the Jianli sub-reach, which is located at the end of the lower Jingjiang reach and has the highest sinuosity in the lower Jingjiang reach, can represent the lower Jingjiang reach for examining channel changes in this study. Fifteen cross-sections at different channel pattern were selected to display the cross-section changes along the Jianli sub-reach (Figure 5.3). From upstream to downstream, the Jianli sub-reach can be divided into 4 types: anabranch meanders (Jing 143, Jing 144, Jing 177), Shangchewan cutoff bend, Yanchuantao straight course, and meander cluster (Xiongjiazhou bend, Baxingzhou bend and Guanyinzhou bend). In addition, three cross-sections at the junction of Dongting Lake and the Jianli sub-reach (Figure 5.3) were also involved in the study for examining the impact of Dongting Lake.

5.2.1 Cross-sections at anabranch meanders

From 1954 to 1969, the left channel was deepened but the right channel was silted at cross-section Jing 143. Similarly, the undercutting also occurred at cross-section Jing 177 (Figure 5.4), the north bank at Jing 177 was washed out from 1964 to 1969 and the thalweg was cut down more than 5 m.

Figure 5.3 *Location of cross-sections along the Jianli sub-reach.*

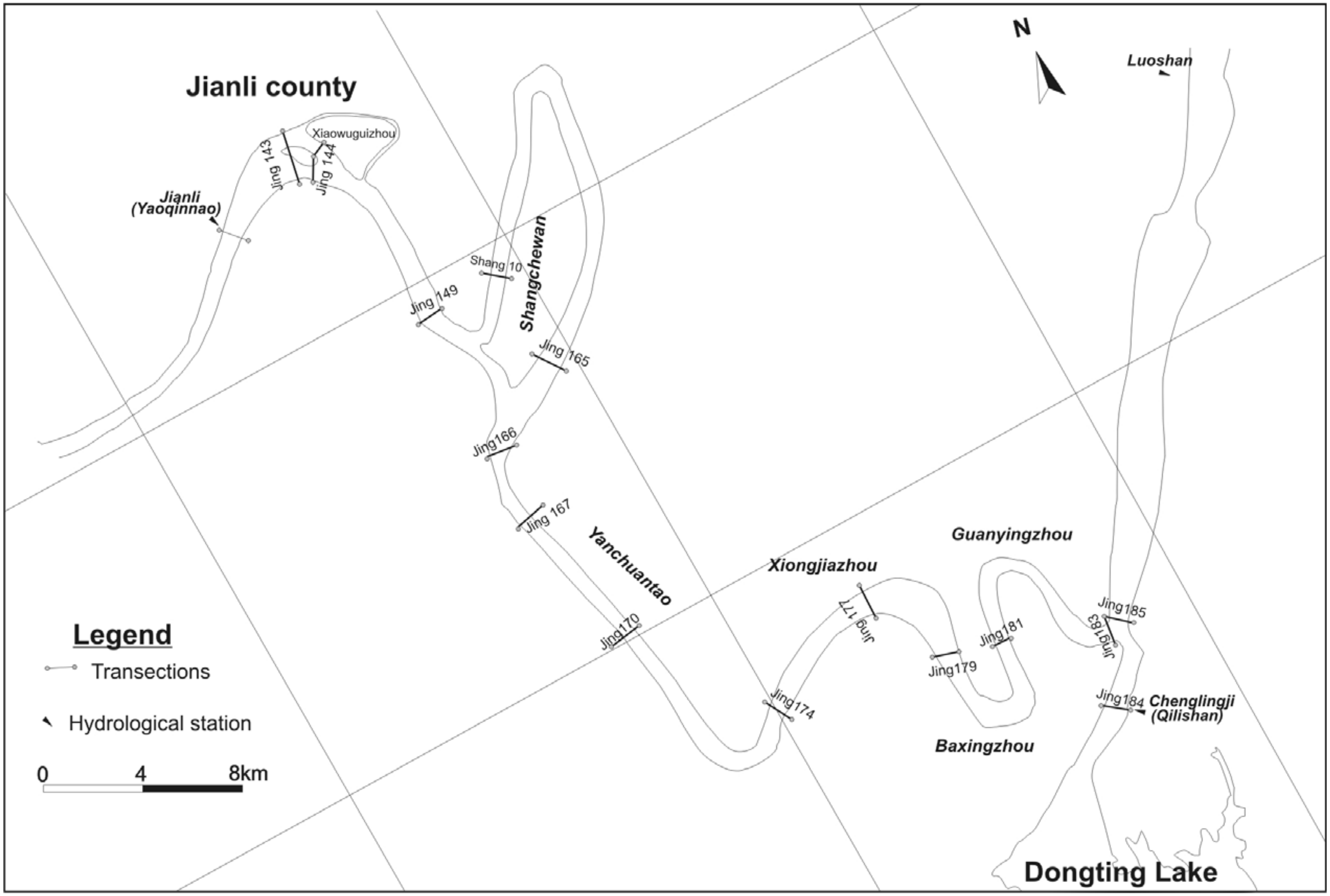


Figure 5.4 ***Cross-sections at anabranch meander. Data source: YWCC cross-section survey data.***

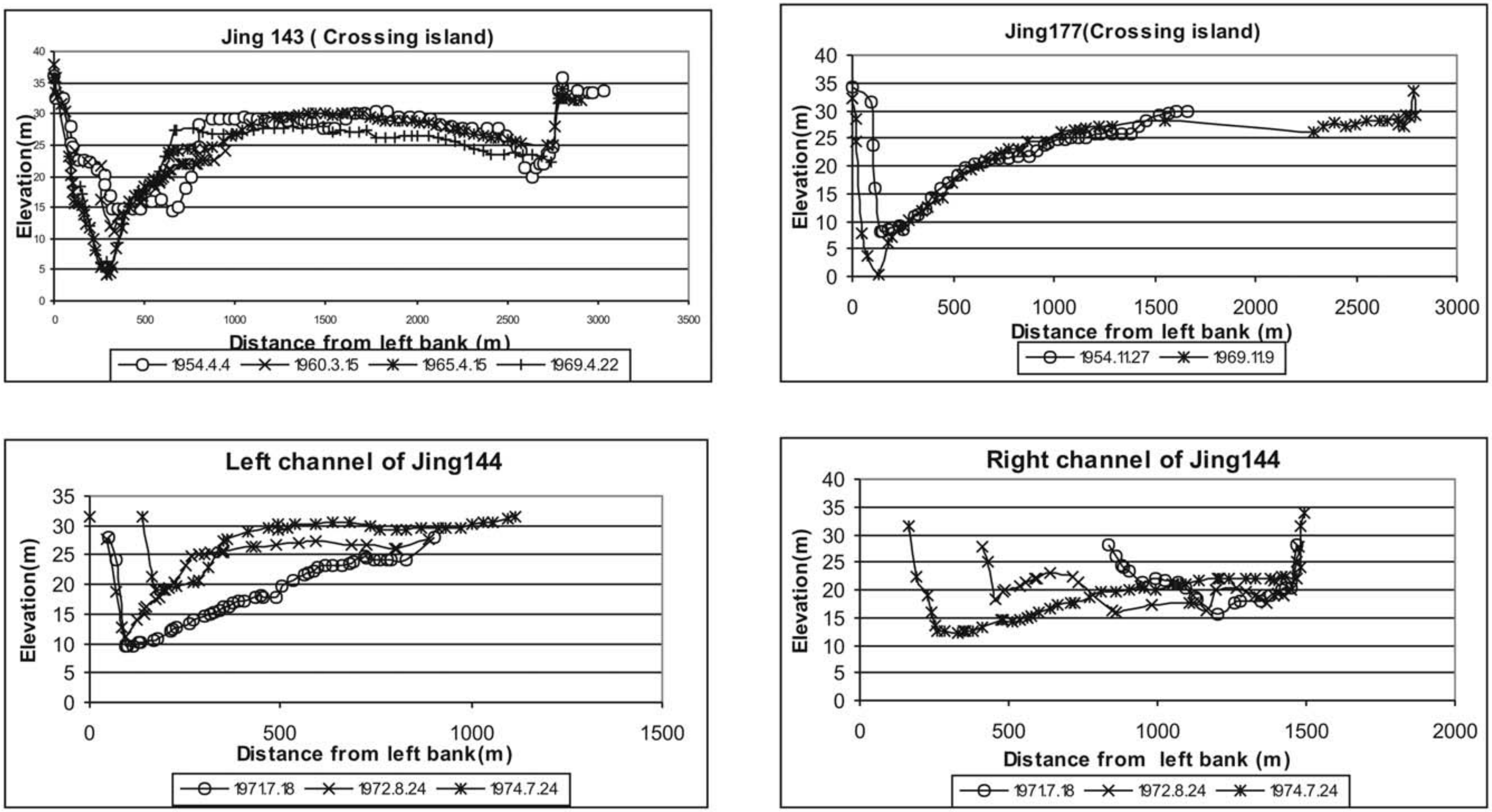
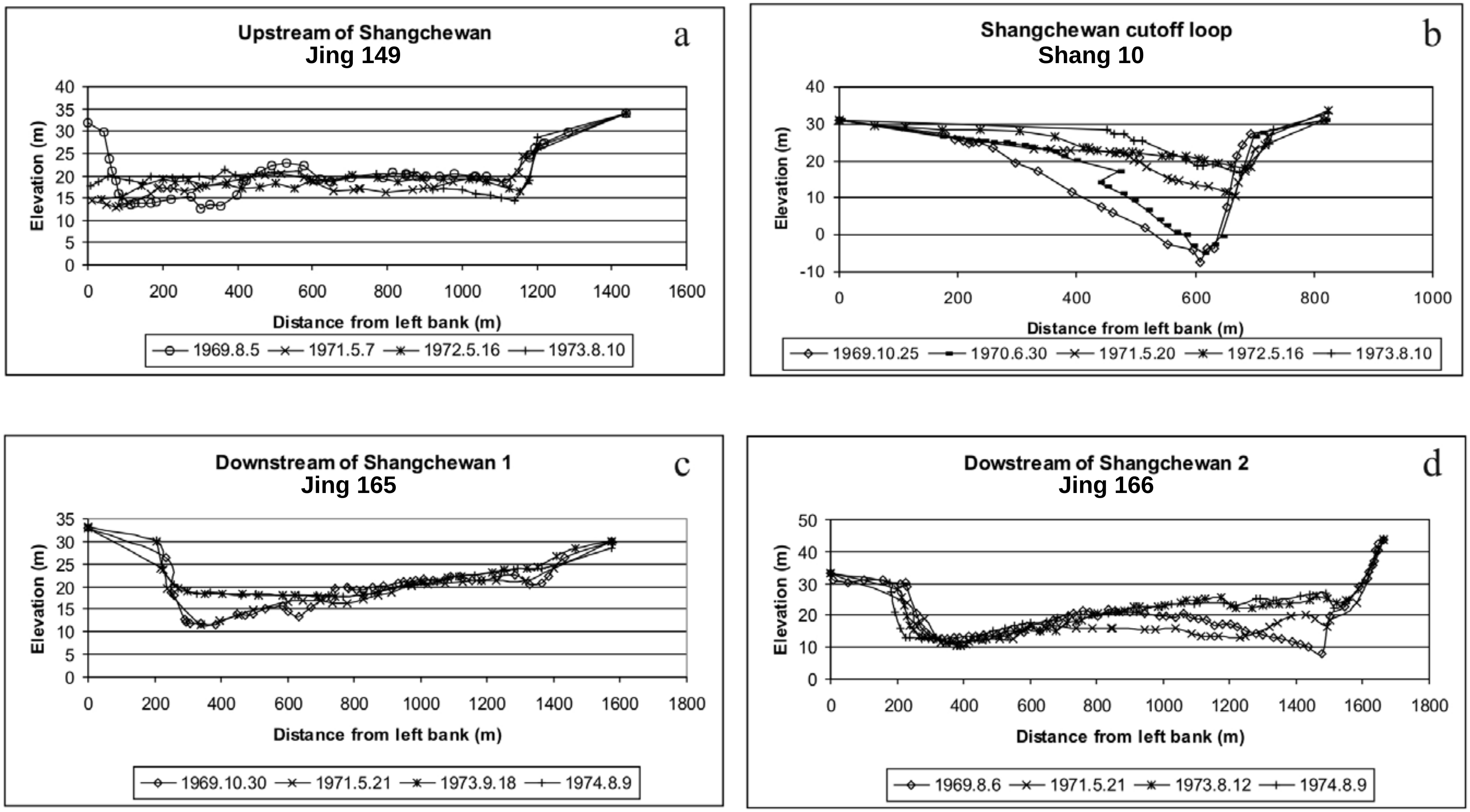


Figure5.5 Cross-section at the Shangchewan cutoff bend. Data source: YWCC cross-section survey data



A mid-channel bar separated trans-section Jing144 into two channels: left (north) channel and right (south) channel. It is obvious that left channel received sedimentation from 1971 to 1974. Channel narrowing and channel aggradation occurred in the left channel, meanwhile the middle channel bar developed with the sedimentation in the right channel. In contrast, right channel had a wider and deeper channel from 1971 to 1974. South bank of the mid-channel bar endured a serious bank collapse, from 1971 to 1972, channel width in the right channel almost doubled from 1971 to 1972, and increased by about 200 m from 1972 to 1974 due to the bank retreating at the north bank of right channel. The significant changes in both channels from 1971 to 1974 may be related with cutoff events in the lower Jingjiang reach, which disturbed the equilibrium status in river channel (Figure 5.4).

5.2.2 Cross-section at the cutoff meander

The profiles of four cross-sections near Shangchewan meander in Figure 5.5 show a general trend of deposition during the implementation of Shangchewan artificial cutoff project. Cross-section at the cutoff bend indicates the continuous siltation in the abandoned bend (Figure 5.5b). Cross-sections at the entrance and exit of Shangchewan cutoff bend display the erosion occurred in the riverbed, especially the central portion in the upper stream cross-section in the first two years after project completion in 1971 (Figure 5.5 a, c, d).

5.2.3 Cross-sections at the straight course

Jing 167 transection is located in the Yanchuantao straight course (Figure 5.3) and represented a scouring in the riverbed, river channel was enlarged and channel depth was deepened (Figure 5.6). The width of bank collapse in the south bank from 1959 to 1970 was about 200 m. The elevation of thalweg fell to below 0 m after 1970. The siltation in the riverbed from 1969 to 1974 can be related to the Shangchewan cutoff event, which was implemented from 1969 to 1970. Similar with Jing 167, profile of Jing 174 also displayed a scouring in the channel valley from 1954 to 1969. Particularly, thalweg in the channel was scoured from 10 m to lower than 0 m (Figure 5.6).

5.2.4 Cross-sections at the meander cluster

Jing 179 and Jing 181 are located at Baxingzhou and Qixingzhou meander loop, degradation and bank collapse occurred in both Jing 179 and Jing 181 from 1954 to 1969. Deposition and erosion coexist in the riverbed of Jing 181, which also had channel-widening tendency from 1954 to 1969 (Figure 5.6).

5.2.5 Cross-sections at the junction

Three cross-sections (Jing 183, Jing 184 and Jing 185) near the joint of the Jianli sub-reach and Dongting Lake were also examined (Figures 5.3). Among these three cross-sections, Jing 184 which is at the mouth of Dongting Lake has the highest thalweg elevation and most stable U-shape channel, Jing 183 at the end of the Jianli sub-reach underwent downcutting in river bed and bank retreat in south bank from 1954 to 1969 (Fig 5.7). Jing 185 has the deepest thalweg in the channel and represented scouring in

Figure 5.6 Cross-section changes at the straight course and meander cluster. Data source: YWCC cross-section survey data

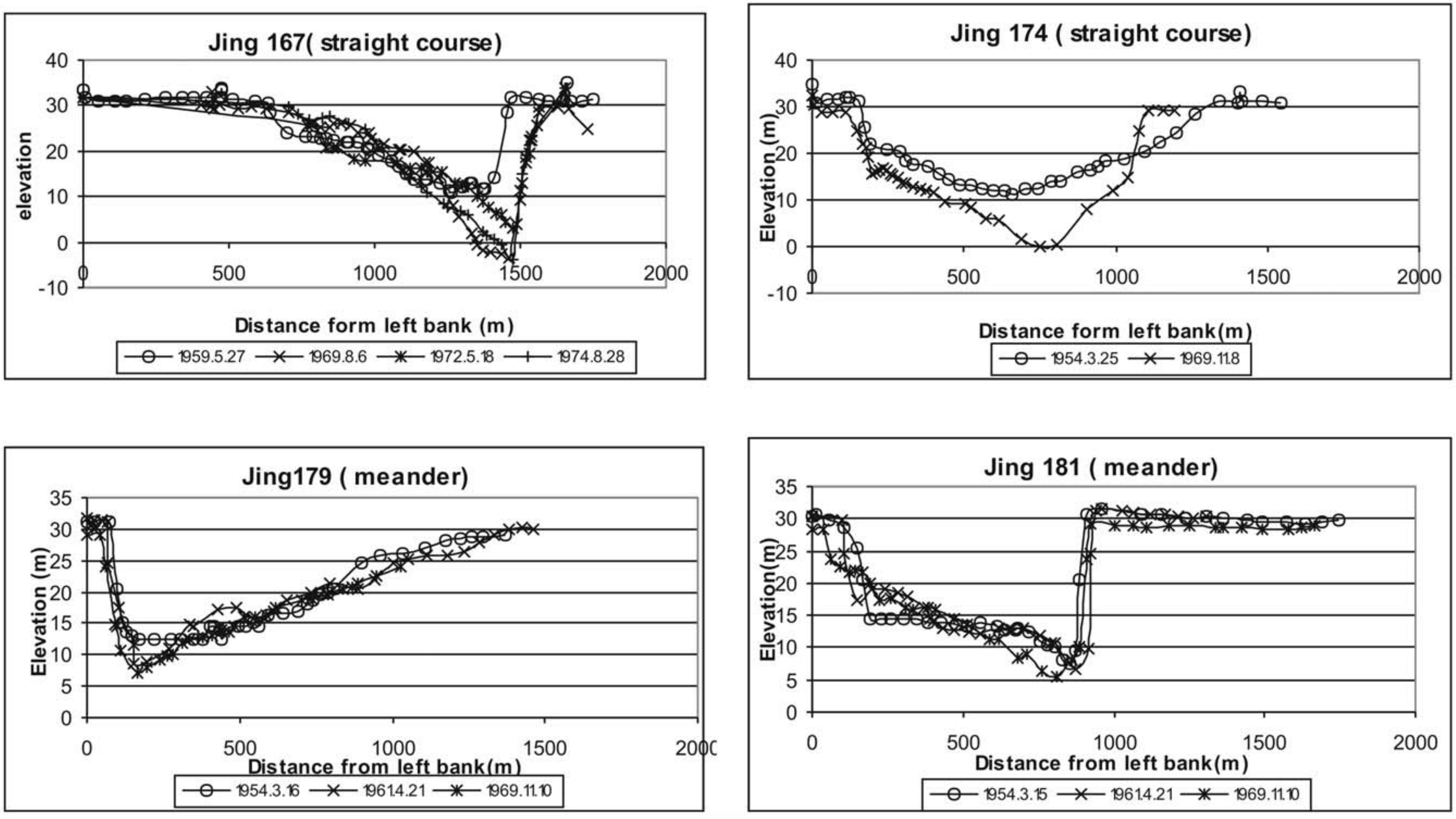
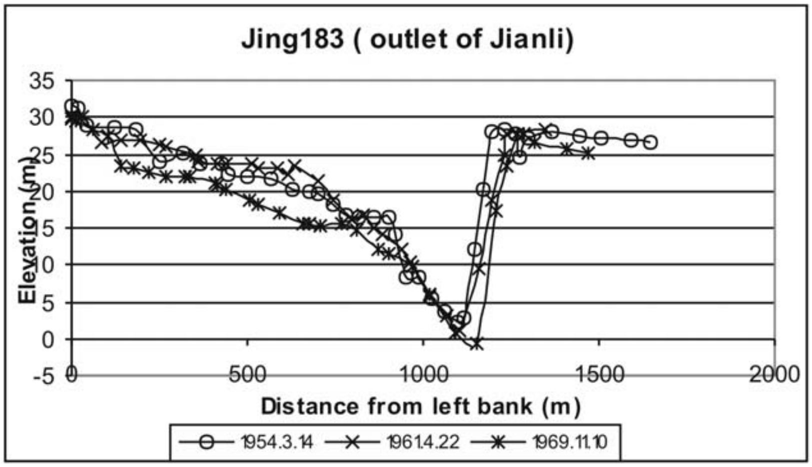
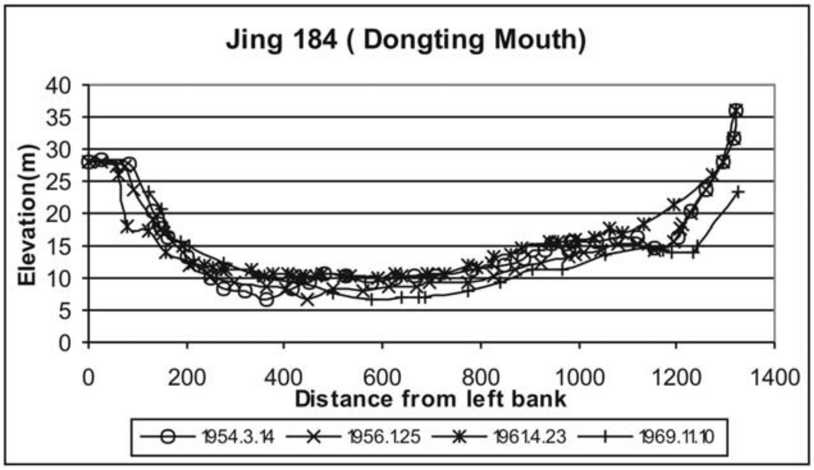
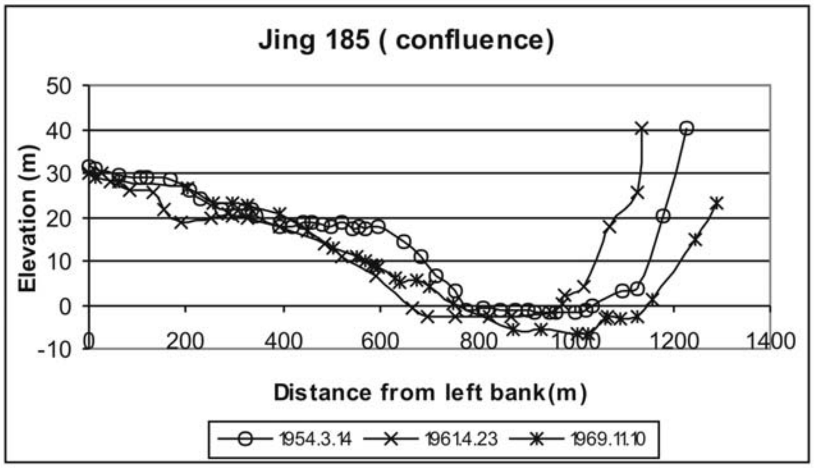


Figure 5.7 Cross-section changes at the junction between Dongting Lake and the Yangtze River







channel valley from 1954 to 1961, till 1969, the thalweg elevation was undercut to -6.8m. Scouring at Jing 183 and Jing 185 may be related with the shrinkage in Dongting Lake and difference in channel elevation (Figure.5.7).

5.3 Conclusion

Cross-sections at major stations along the middle Yangtze River showed that Yichang and Hankou had rather stable cross-sections from 1966 to 1987, and the most varied reach was at the lower Jingjiang reach. This may be related with the hydrology regime changes and different channel patterns along the Jingjiang reach.

Fifteen cross-sections along the Jianli sub-reach in the lower Jingjiang reach presented a phenomenon of undercutting in the riverbed and bank retreating along the Jianli sub-reach from 1950s to 1980s. Furthermore, meander bends are more susceptible than relatively straight course. Particularly, undercutting at upstream and downstream deteriorated after the Shangchewan cutoff event, while undercutting at the main stem near the junction between Dongting Lake and the Yangtze River.

However, all the cross-sections in this chapter were based on the hydrological survey data, which is not available after 1987. Channel changes after 1987 can be only discussed on the basis of other data source.

Chapter 6. RIVER CHANNEL CHANGES DERIVED FROM GIS ANALYSIS

6.1 Introduction

The cross-sectional changes before 1987 in the study area have been presented in Chapter 5 based on the hydrological survey. As the post-1987 hydrological survey data were not published by YWCC, cross-section changes after 1987 along the study reach can be only reconstructed based on map sources. With the application of GIS technique, historical map sources can outline channel changes over a longer time than the expensive systematic field survey data, which has been presented in Chapter 5. This chapter aims to elucidate river channel changes along the study reach during the last 50 years from three aspects: channel planform changes, cross-sectional change and erosion/deposition patterns.

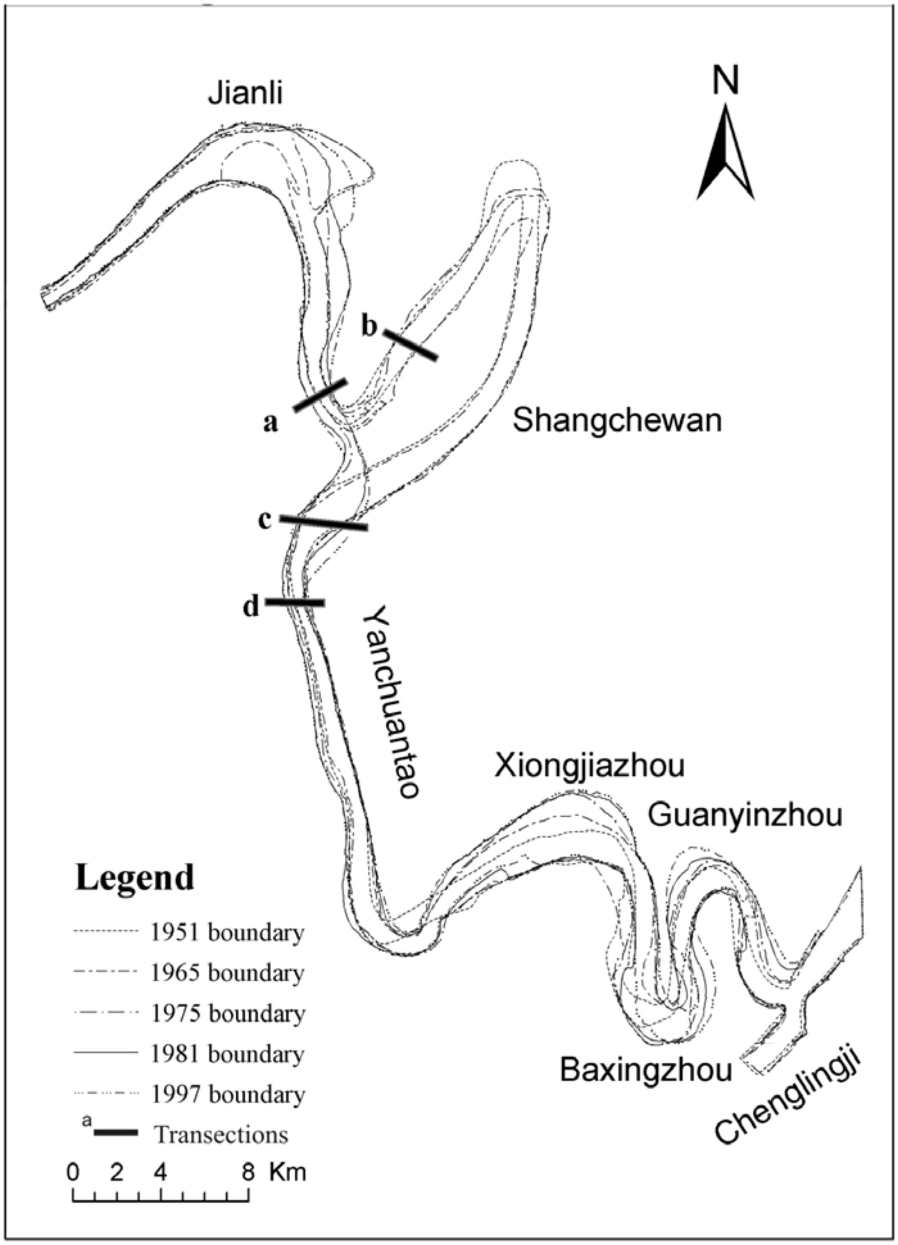
6.2 Channel planform change from 1951-1997

6.2.1 Channel migration from 1951 to 1997

Bank migration in the last five decades in the study area can be seen from the reconstructed river boundaries (Fig 6.1). Given the existence of levees along the riverbanks in the middle Yangtze River, the river channel pattern change from a meandering river to braided river is impossible. The most obvious planform change was at Shangchewan bend, which was artificially cut off for the purpose of flood protection and navigation at the end of 1960s. The abandoned river bend was out of navigational use because of siltation in the channel and vanished from the navigation charts after 1981 (Fig 6.1). In addition, there is a minor channel widening trend from 1951 to 1997, since major shifts and channel pattern change are impossible under the constraints of the constructed levees. For example, the average channel width increased by 66 m, even though the average channel width ranges from 900 m to 1700 m, while the area of river channel increased 6.5 km^2 from 1981 to 1997.

Chronologically, the river channel in the Jianli sub-reach has undergone three stages of development/gradation. The first stage is the pre-cutoff stage (1951-1969). Shangchewan bend had the greatest sinuosity (5.07), which favours the deposition in the bend. Meanwhile, as the exits of the meander are subject to greater shear stress, which scours the inner bank and initiate bank collapse, there is a tendency of channel widening at the exits. Over these 15 years, for example, cross-section 6 was widened from 516m to 1858m. The second stage is the roily period of the implementation of the cutoff project (1969-1980). Shangchewan bend was separated from the main chute. Water flow rushed down through the new cannel and scours the riverbed of the new channel. Hence, channel widening occurred upstream and downstream of the cutoff site (Fig 6.1). As the Yanchuantao course downstream of the Shangchewan bend is a straight channel, the effect of the Shangchewan cutoff event can be delivered to the consecutive meanders (Xiongjiazhou, Baxingzhou, and Guiyingzhou). The migration of these meanders is the

Fig 6.1. Bank migration in the study reach from1951 to1997. River boundary of 1951, 1965 and 1975 are extracted from channel evolution map (1:100,000), those of 1981 and 1997 are from navigation charts (1: 25,000)



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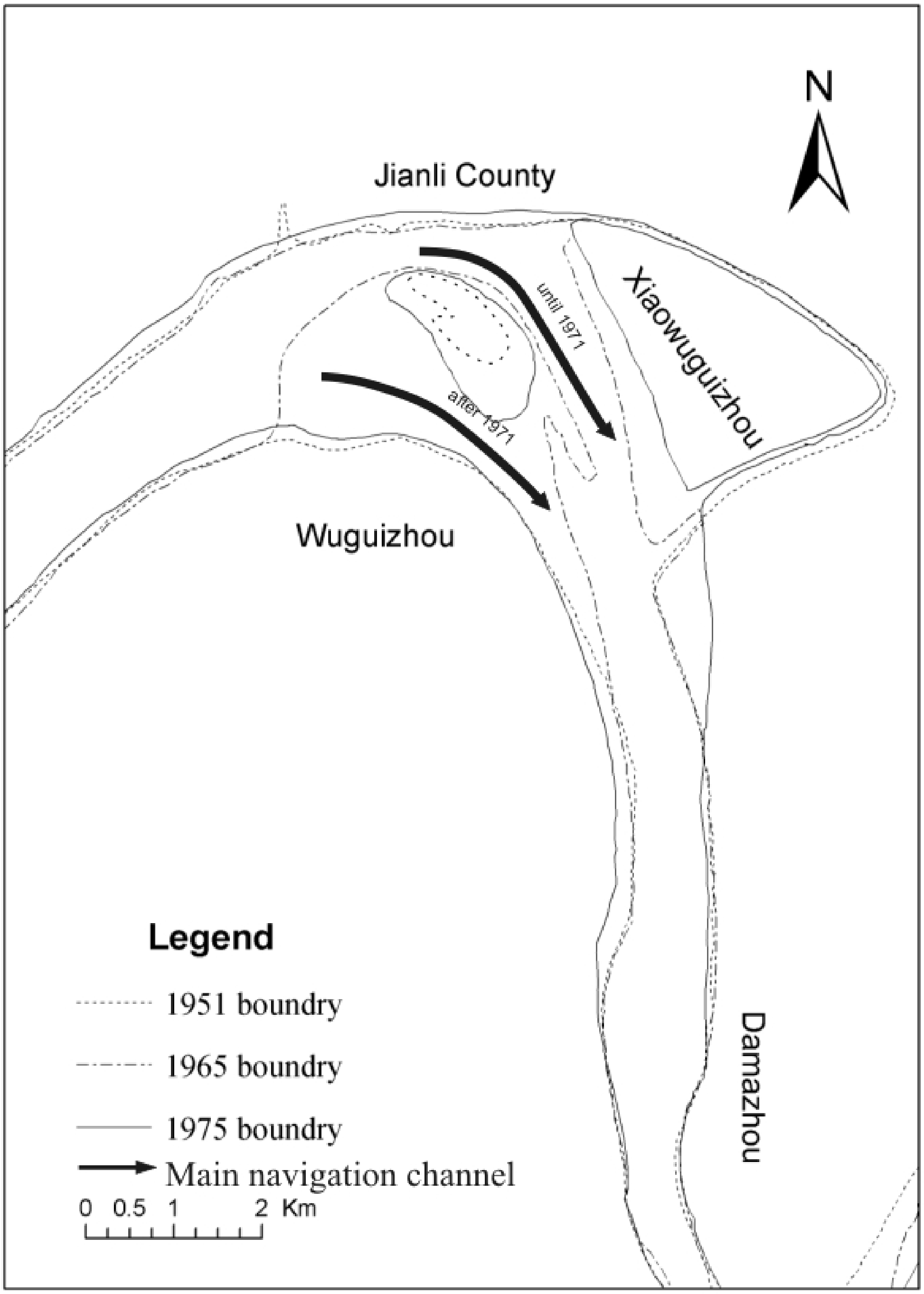
best evidence of the upset equilibrium perturbed by the cutoff event. The third stage (1981-1997) is the stage when the river channel retrieved a new equilibrium from cutoff events. The evidence from hydrological data revealed that the Jianli sub-reach had recovered from the cutoff events (Li and Ni, 1998). In general, the whole reach was in a relatively stable plan form except for the shift of the navigation channel due to siltation in the north branch.

The shift of navigation channel in the Jianli bend from 1951 to 1975 was shown in Figure 6.2. The navigation channel was divided into north channel and south channel by a mid-channel bar at this bend in 1951. It was recorded in the navigation charts that the major navigation channel was the north channel until the cut-off in 1971 when the sediment bar in the middle of the channel was washed out as a separate island in the channel (WNB, 1983). The south margin of the island was washed out and collapsed; the south channel migrated northward and became the main navigation channel in drought season until 1975 (Figure 6.2). From then on, the navigation channel had shifted between north channel and south channel periodically. In 1981, there were actually three bars, Wuguzihou, Xiaowuguizhou and an un-named mid-channel bar between them. From 1981 to 1997, this mid-channel bar attached with Wuguizhou and became the edge of south bank, while the small channel behind Xiaowuguizhou was blocked because of long-time small discharge flows and long-time sedimentation due to low velocity flow. However, the main stem of Yangtze flow washed out the edge of Xiaowuguizhou and brought away the loosen material (see Fig 6.2).

Figure 6. 2. *Navigation channel shift in the Jianli bend from 1951- 1975.*



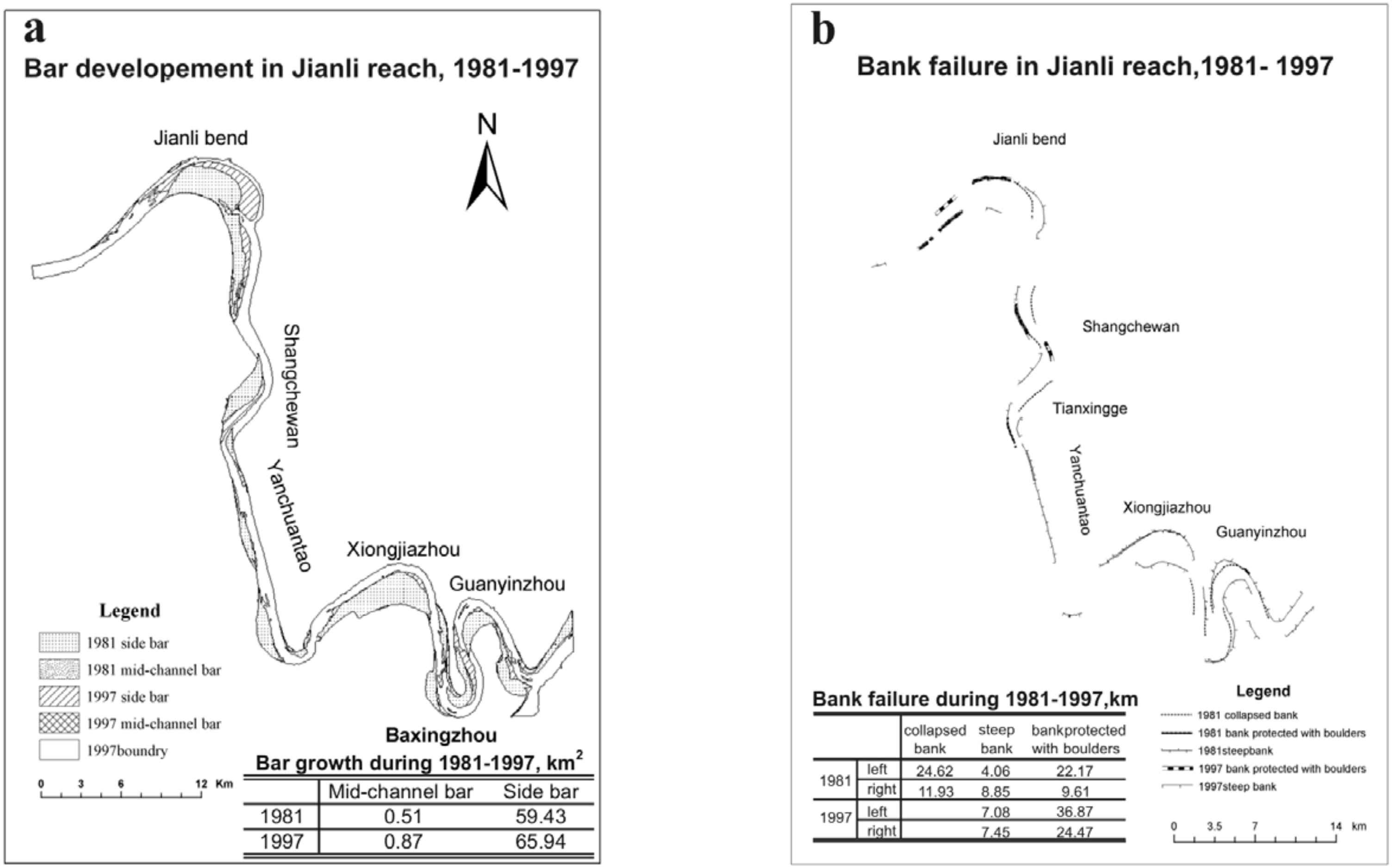
6.2.2 Bar development from 1981 to 1997

The bar development and bank erosion contributed to the minor channel widening in study reach (Figure 6.3). The area of the mid-channel bar increased by 0.36 km^2, and the area of the side bar increased by 6.5 km^2 from 1981 to 1997(Figure 6.3a). Features of bar development in this reach are first that the islands or bars headed downstream; second that the bar develops dramatically at meander bends, third that bar development leads to channel widening (Figure 6.1). The river surface area of the entire Jianli sub-reach increased by 11 km^2, and the eroded area was 8.2 km^2 larger than the deposited area from 1981 to 1997.

6.2.3 Bank failure from 1981 to 1997

In 1981, the total length of collapsed bank was around 36.5 km, taking up 33% of the length of the Jianli sub-reach. The collapsed portion along the north bank (24.6 km) was longer than that along south bank (11.9 km) (Figure 6.3b). These collapsed banks disappeared from the 1997 navigation charts due to the bank protection works from 1982 to 1985. The rocky bank at the north bank increased from 4km to 7 km, while the south bank decreased from 8.8 km to 7.4 km from 1981 to 1997(Figure 6.3b). The eliminated rocky bank was in the straight Yanchuantao course and the new rocky bank appeared at the outer bank of Jianli bend. At the same time, the length of the steep bank along both banks rose greatly, around 15 km along each bank. Yang and Tang (1998) estimated the rate of retreat of collapsed bank line was 35.2 m/a in the study reach. It can be estimated that

Figure 6.3 ***a) Bar development in the study reach from 1981 to 1997. b) Bank failure in the study reach from 1981 to 1997.***



Bar growth during 1981-1997, km^2

	Mid-channel bar	Side bar
1981	0.51	59.43
1997	0.87	65.94

Bank failure during 1981-1997,km

		collapsed bank	steep bank	bankprotected with boulders
1981	left	24.62	4.06	22.17
	right	11.93	8.85	9.61
1997	left		7.08	36.87
	right		7.45	24.47

2.77 km^2 of the bank experienced collapse after 1981, while the total area of collapsed bank up to 1997 was 45 km^2. These collapsed bank materials may be deposited in the riverbed to facilitate the development of the bar in the river. Vanished collapsed banks were located near the cut-off site or along the Yanchuantao course. On the contrary, the newly collapsed banks along south bank are always related to the concave bank of meander bends. The concave bank is susceptible because of the high shear force and friction in the meander, while banks along the straight course are more resistant.

6.3 Cross-section change from 1981 to 1997

6.3.1 DEM and longitude profiles

DEMs based on navigation charts in 1981 and 1997 are critical for providing the information about changes in channel geometry and bed topography (Figure 6.4). The range of vertical elevation in 1997 is wider (from –43 m to 20 m) than that (from –30 m to 14 m) in 1981 (Figure 6.4), suggesting that the roughness of the riverbed in 1997 is higher. The longitude profiles along the referred navigation route were extracted from 2 DEMs and also indicated the changes in the vertical profiles. The mid-channel bar emerged and the riverbed was scoured from 1981 to 1997.

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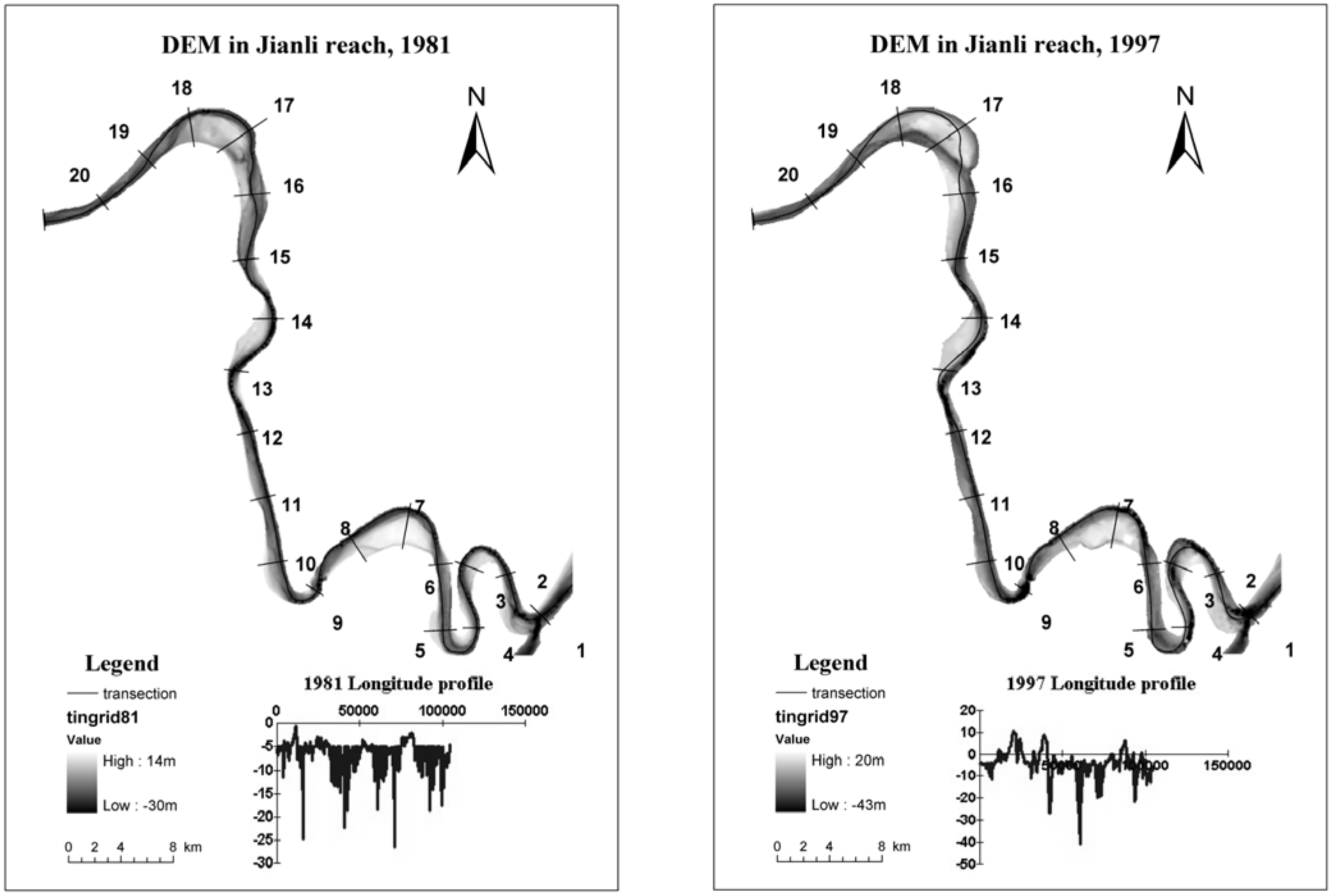
Fig 6.4. ***Grid of DEMs and longitude profiles in the study reach in 1981 and 1997. Longitude profiles were both interpolated along the navigation reference route in 1981.***



6.3.2 Cross-sections with 5 km interval

The cross-sections at twenty sites are extracted from the two DEMs (Figure 6.5). As was proposed by Leopold and Wolman (1960), the deep thalweg along meandering bend is located along the outer concave bank, but the point bar attached with inner bank due to the interaction between helical flow and primary longitudinal flow, such as the cross-sections 3, 4, 5, 7, 8, 17. Riverbed scouring below navigation reference plane dominates most of the cross-sections except cross-sections 10 and 11, which are located at the Yanchuantao straight watercourse. In contrast, obvious depositions above the reference plane can be seen at the cross-sections of 13, 15, 16 and 17 at the meander bends. The channel geometry in the Yanchuantao course is relatively stable, like at cross-sections 10 and 11. Furthermore, channel widening can be also observed from many of the cross-sections, such as the cross-sections 3, 9, 12, 13, 14 15 17 and 18 (Figure 6.5).

6.4 Erosion/deposition pattern

6.4.1 Planar erosion/deposition area

It is estimated that the total erosion area during 1981-1997 in the Jianli sub-reach is about 16 km^2, while the deposited area is around 10 km^2 (Figure 6.6a). Erosion mainly occurred at the concave bank of the meander bends, while deposition took place at the convex bank, such as the Xiongjiazhou and Chibakou bend (Figure 6.6a).

Figure 6.5 Cross-sectional changes derived from DEMs in 1981 and 1997.

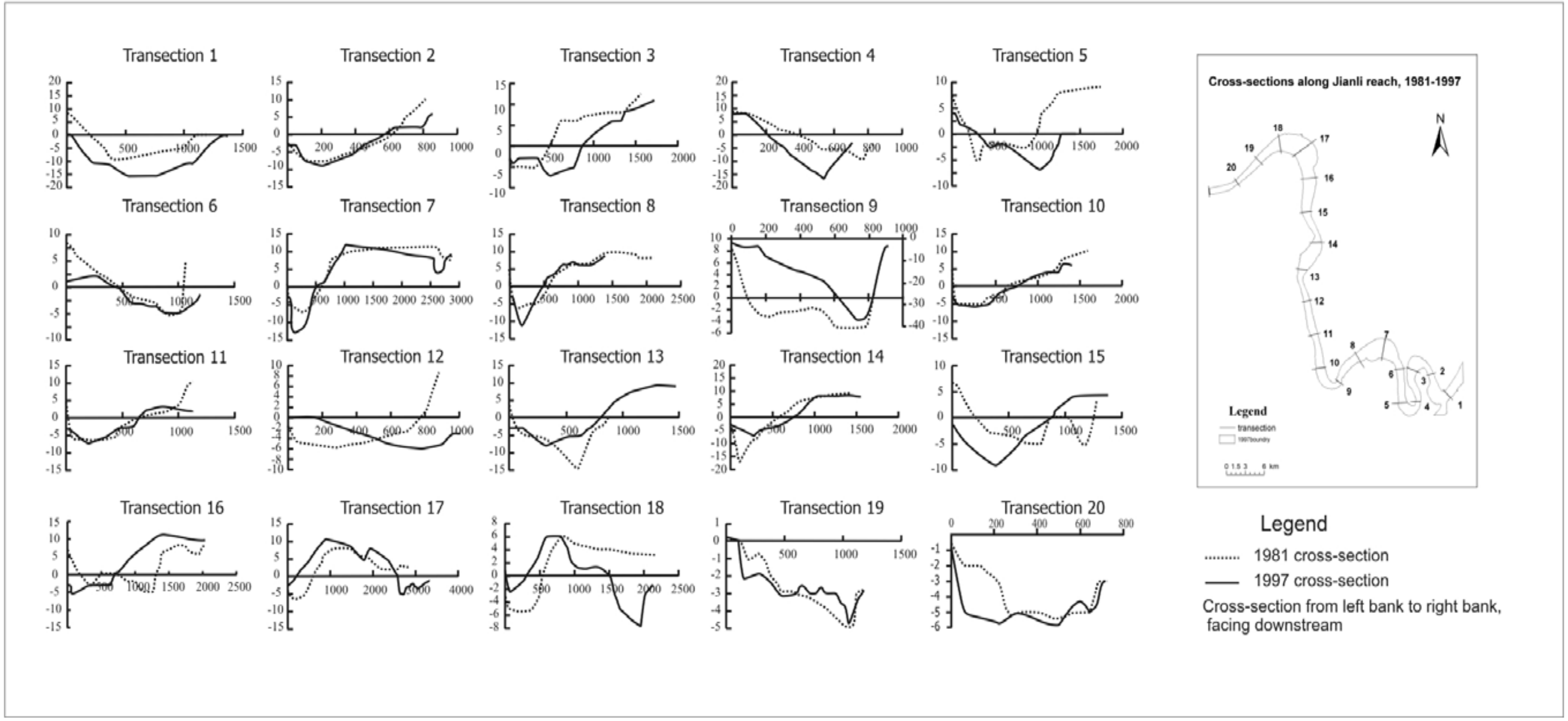


Figure 6.6 Erosion/depostion area in the Jianli sub-reach

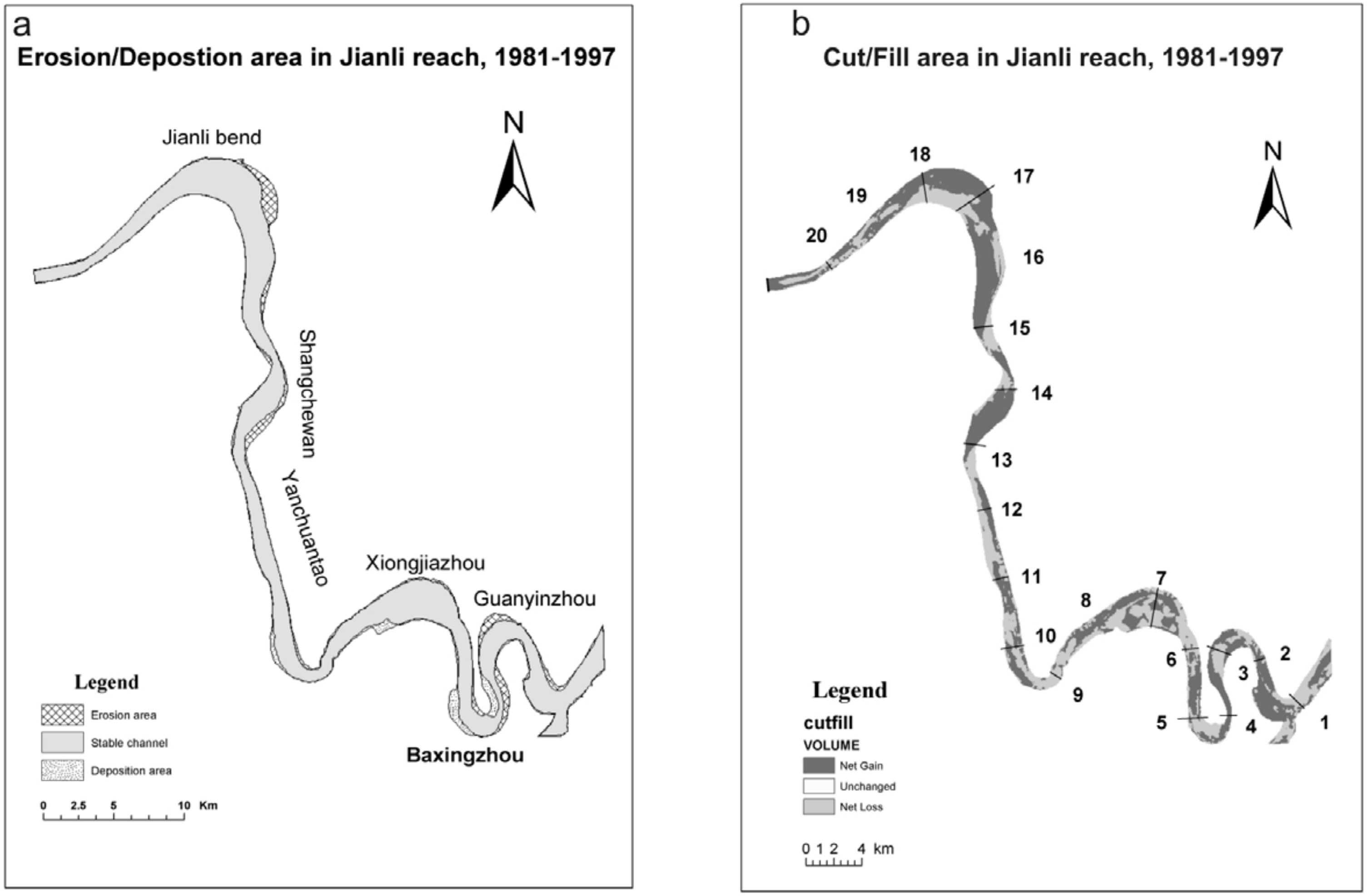


Table 6.1 Cut/fill area and volume from 1981 to 1997.

Cut/Fill	Volume (km^3)	Area(km^2)
Cut	0.19	57.06
Fill	-0.27	72.22
No change	0	13.36

6.4.2 Vertical erosion/deposition area (cut/fill area)

The cut/fill area indicated the location of erosion/deposition occurring in the stable channel (the "stable channel" portion in Figure 6.6a) from 1981 to 1997 (Figure 6.6b). Table 6.1 tells that in the "stable channel", more sediment was silted in the "stable channel" rather than washed out of the channel from 1981 to 1997. The cut area was also smaller than the fill area (Table 6.1). The net gain area mainly was located at the outer bank of meanders, while the net loss area was at the opposite bank. Particularly, the Jianli bend and Damazhou were dominated by the accretion, whereas the Xiongjiazhou bend was dominated by degradation (Figure 6.6b).

6.4.3 Volume calculation

The volume of erosion and deposition derived from the 2 DEMs in 1981 and 1997, using the navigation reference plane as benchmark, presents the pattern of "overbank deposition, in-channel erosion". About 50 million m^3 of sediment was deposited above the reference plane, while about 55 million m^3 of sediment was washed out from the channel below the reference plane from 1981 to 1997 (Table 6.2). The difference between the surface area and 2D area indicated that the surface below the navigation reference plane was rougher and steeper than above the plane in 1981 and 1997, and that the surface below the reference plane became rougher and steeper from 1981 to 1997, while the surface above it became flatter and gentler (Table 6.1). These results present an over-bank deposition and riverbed incision pattern during 1981-1997.

Table 6.2 ***The surface area and volume of erosion and sediment deposition from 1981 to 1997.***

	2D Area (km^2)	Surface Area (km^2)	Volume (km^3)	SA-2DA(km^2)
1981 above 0m	62.21	62.25	0.33	0.04
1981 below 0m	76.02	76.09	0.32	0.07
1997 above 0m	67.52	67.54	0.38	0.02
1997 below 0m	78.24	78.33	0.37	0.09
1997-1981 above 0m	5.31	5.29	0.05	-0.02
1997-1981 below 0m	2.22	2.24	0.06	0.02

6.5 Conclusion

Results based on map materials displayed a slight channel widening from 1951 to 1997, as major channel pattern change is impossible under the control of levees along both banks. Serious bank erosion was observed by comparing bank type and river boundaries in different years. Twenty Cross-sections extracted from DEMs illustrated that the erosion/deposition pattern along the Jianli sub-reach is “overbank sedimentation and in-channel erosion”, and also indicated that cross-section changes are related to their location. GIS helps to quantify the area and volume of erosion/deposition, together with positioning the location of erosion/deposition area. Basically, bank retreat occurs at the outer bank of meanders, while bank advance at the inner bank. The straight channel is relatively more stable than meanders in terms of the erosion/deposition area and cut/fill area. Furthermore, the volume of sedimentation above the benchmark (navigation reference plane) is smaller than that of erosion below the benchmark. A deeper thalweg in 1997 also indicates the erosion in the channel.

Chapter 7. DISCUSSION

7.1 Increased water discharge and sediment load enhance bank erosion

7.1.1 Increased water discharge

It is shown in Table 7.1 that mean annual water discharge along the Jianli sub-reach increased gradually from 1956 to 1997 at the Jianli station, but decreased at the Qilishan station, which is located at the mouth of Dongting Lake (Figure 5.1). This can be related with the Dongting shrinkage since the 1950s. As the water flow from upper stream is diverted into Dongting Lake before passing through the lower Jingjiang reach (Figure 5.1), the Dongting shrinkage due to lake reclamation represents a great loss of modulation volume of Dongting Lake and results in more water from upstream flows into the Jianli sub-reach not into Dongting Lake (refer to Chapter 3).

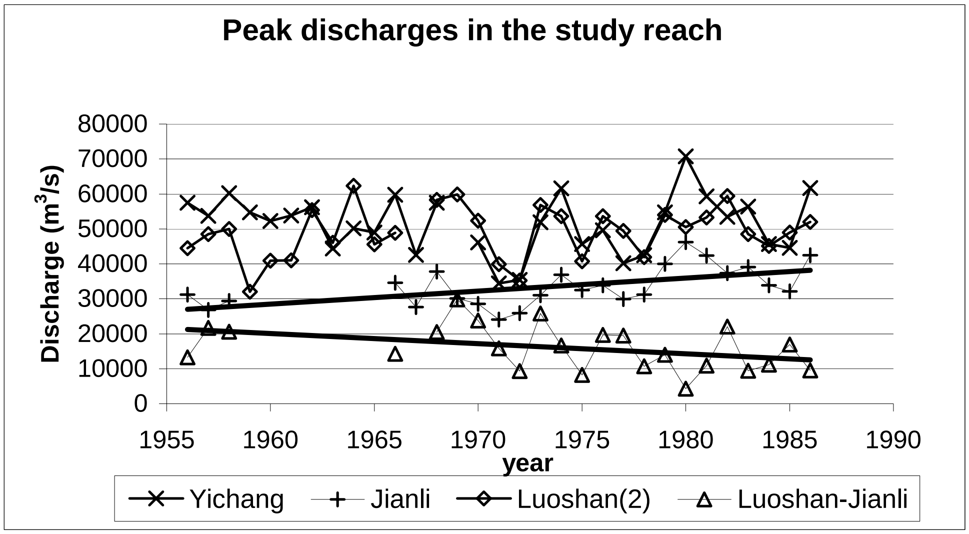
Besides annual water discharge, peak discharge is another important parameter as it is one indicator of flood characteristics. The safety capacity of the Jingjiang's river channel can approximately withstand the peak flow of 60,000 m^3/s entering to the reach at Zhicheng, including the diversion to Dongting Lake (Luk and Whitney, 1993). However, according to recorded data from 1877, peak discharge at the Yichang has surpassed 60,000 m^3/s more than 24 times (Zhang *et al*., 2000).

Table7. 1 Yearly water discharge, sediment load and water level in the study reach. Bold data are adopted from Yang and Tang, 1998

	Mean annual water discharge (m^3/s)				Mean annual sediment load (kg/s)				Mean annual water level (m)			
Station	1951-1965	1966-1975	1976-1981	1982-1997	1951-1965	1966-1975	1976-1981	1982-1997	1951-1965	1966-1975	1976-1981	1982-1997
Jianli	**10207**	11002	11333	12100	**9820**	**NA**	13200	10220	28.36	28.00	28.07	28.24
Qilishan	**9912**	8460	9260	8372	**1910**		1310	1124	**24.22**		NA	25.22
Luoshan	**19941**	20178	19400	NA	**13100**		15450	NA	23.1	23.36	23.31	NA

During last half century of 20th century, peak discharge beyond safety capacity at the Yichang station occurred in 1954, 1958, 1974, 1980, 1986 and 1998 (Figure 7.1). Contradiction between the discharge capacity and floods from upstream along the whole Yangtze River is the severest at the Jingjiang reach (Zhang *et al*., 2000).

Figure 7.1 ***Changes in maximum water discharge in the study reach. (Data source: Yangtze Hydrological Yearbook)***



Basically, the Yichang station, the first station along the Yangtze, and the Luoshan station immediately downstream of the junction between the Jianli sub-reach and Dongting Lake have the synchronous fluctuation of maximum discharge from 1956 to 1986 (Figure 7.1). Peak discharge at the Jianli station has a tendency of increase; contrarily a falling tendency appeared in the Dongting outflow at the Qilishan station from 1956 to 1986 (Figure7.1). This is related to the decrease of Dongting Lake capacity due to lake reclamation in the last 50 years. The falling tendency of "Luoshan-

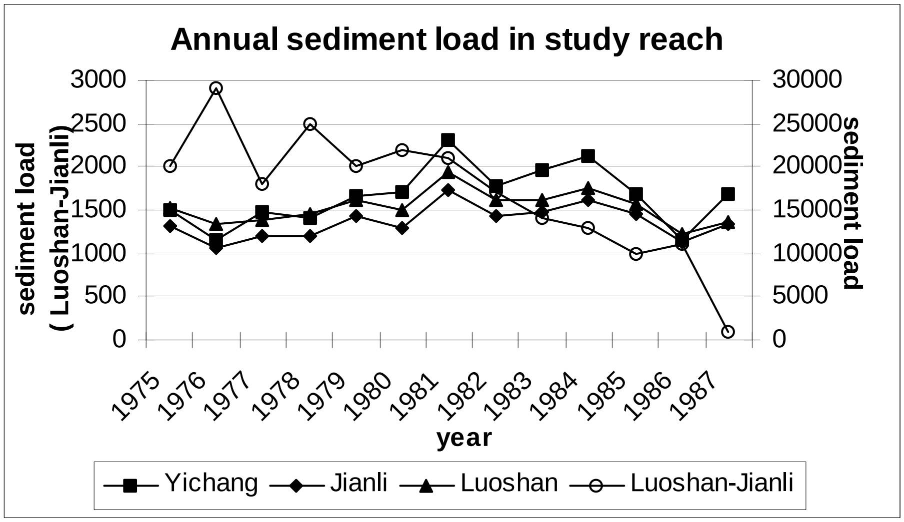
Jianli" suggests the reduction of water supply from Dongting Lake to the Yangtze mainstream.

7.1.2 Increased suspended sediment load

The Yangtze sediment flux is overwhelmed by suspended sediment load, taking up about 96% of the total sediment load (Chen *et al*., 2001b). Suspended sediment load declines from the Yichang station in the upper reach to the Jianli station and the Luoshan station in the middle reach (Figure 7.2). This is because of the deposition of suspended sediments while water flows downstream. Suspended sediment load at the Yichang station averages 5.16×10^8 t/a, of which 1.4×10^8 t/a is deposited in Dongting Lake (Tang and Xiong, 1998; Du *et al*., 2001; Xiang *et al*., 2002). The synchronous fluctuation and difference in amount of sediment load at the Yichang, Jianli and Luoshan stations (Figure 7.2) indicate that the sediment source of the middle Yangtze River is mainly from the upper basin. The Luoshan station has greater sediment load than the Jianli station upperstream, due to the confluence with Dongting outflow. The declination in difference of sediment load between the Luoshan station and the Jianli station (Figure 7.2) suggests the sedimentation in the Jianli sub-reach and the Dongting Lake.

Similar with mean annual water discharge, mean annual suspended sediment load increased gradually from 1956 to 1997 at the Jianli station, but decreased at Qilishan, which is located at the mouth of Dongting Lake (Table 7.1). This can be also attributed to the sedimentation in the Dongting Lake. The sedimentation in the Dongting Lake is very significant that in the Dongting Lake, lake area had decreased from 4350 km^2 to 2623 km^2, lake capacity reduced from 293×10^8 m^3 to 167×10^8 m^3 from 1949 to 1995. Hence, more sediments and water were transported through Yangtze mainstream, and less in Dongting Lake.

Figure 7.2 ***Annual sediment transportation in the study area. (Data source: Yangtze Hydrological Yearbook).***



7.1.3 Severe bank erosion

Increase in water discharge promotes the increase in boundary shear stress (Petts and Amoros, 1984). As a result of sedimentation in Dongting Lake, more water and sediment has been transported through the Yangtze main stem (refer to Jianli reach). Greater water discharge in the Jianli sub-reach (Table 7.1 and Figure 7.1) promoted the scouring within river channel and initiated severe bank migration and channel widening (Figure 6.1). On the other hand, higher suspended sediment load from Shishou reach immediately upstream of the Jianli sub-reach and local bank collapses provide plenty of sediments for the growth of point bars in the channel (Figure 6.3a), which will, in turn, reduce the capacity of river channel and further intensify the friction between water flow and river channel.

Bank collapse is initiated by a change of hydrologic regime of a river but is determined by the susceptibility of bank material (Knighton, 1984; Lawler *et al*., 1999). Banks along the Jianli sub-reach are composed of sand and silt. Composite bank structure and helical flow in meanders facilitate bank failure in the study reach, as the cohesive material at bank toe is very susceptible to erosion (Yang and Tang, 1998). Severe bank erosion was observed along the Jianli sub-reach (Shi *et al*., 2002; Ma *et al*., 2000;Yue and Yu, 2002) (Plate 4). Among the meanders along the Jianli sub-reach, Jianli bend has severe bank collapse. Bank along Xiaowuguizhou in the Jianli bend was retreated to 600-1500 m behind the original bank line from 1965 to 1984 (Figure 5.4 Jing144 right). DEMs in 1981 and 1997 depicted that the total length of collapsed bank was around 36.5 km, taking up 33% of the length of the whole Jianli sub-reach in 1981. Collapsed portion along north bank (24.6 km) was longer than that along south bank (11.9 km) (Figure 6.3b). These collapsed banks were either transformed into natural bank due to the successive bank protection from 1982 to 1985 or further eroded into steep bank (Figure 6.3b).

Bank failure has several other effects on river channel. First of all, the channel geometry will change after bank failure due to the alteration in cross-sections. Second, bank failure in flood events may induce the collapse of levee on the bank directly, or reduce the area between waterfront and levee, which would enhance the potential of levee saturation, seepage and levee collapse. Third, failed bank materials will provide river channel massive foreign sediment source further affecting channel evolution in aspect of channel widening and bar growth (Simon *et al*., 1991; Lisle and Madej, 1992). For instance, total bar area in the Jianli sub-reach increased 7 km^2 from 1981 to 1997 (Figure 6.3a). In addition, without timely bank protection, collapsed bank increased the shear stress and benefited the development of meander bends. The evolution of Guanyinzhou bend is a good example (Figure 6.1).

Plates 4 Bank erosion in flood season (Taken in July, 2004).

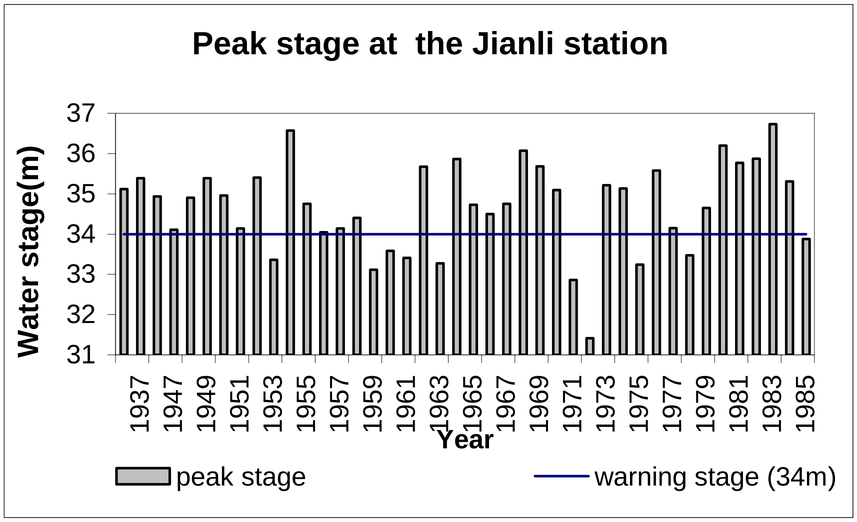
7.2 Extensive overbank flows facilitate deposition over riverbank and undercutting in riverbed

7.2.1 Extensive overbank flows

The intense overbank flows in the study reach can be represented by the changes in annual water level. Annual water level at Jianli station decreased from 1951-1997, and increased at the Qilishan station, but annual water discharge increased at the Jianli station and decreased at the Qilishan station(Table 7.1). This phenomenon suggests undercutting at the Jianli station and siltation in Qilishan station. Compare to the Jianli station and Qilishan, the Luoshan station immediately downstream of the Jianli sub-reach is in a more stable status. This can be attributed to its geographic position. The Luoshan station recieves outflow from Dongting Lake and mainstream from the Jianli sub-reach, because it has a lower elevation than the Qilishan and Jianli station (Figure 5.7). Thus Luoshan station admits stable amount of water discharge and have a much stable cross-sections (Figure 5.2).

Besides annual water level, peak stage variation also influences river channel changes. The warning stage at the Jianli monitoring station is 34m, however, from 1937 to 1986, peak stage at the Jianli station has surpassed 34m for 40 times (Figure 7.3). YWCC statistics records on the highest water stage at the Jianli station show that during a period of the 37 years (1949-1985), the Jianli station suffered water stage above the warning stage in 25 years and the leading time of warning stage became longer and longer (JLAC, 1991). On one hand, these high stage flows modify the topography on flood plain. On the other hand, these high water stages threatened the safety of levees on the banks and put effect on the adjustment in the channel.

Figure 7.3 ***Peak stage at the Jianli station. (Based on the data from Jianli Levee Archive)***



The decreasing lake capacity on Jianghan fluvial plain greatly affected the conveyance of floodwater in the channel of the Yangtze main stem (Wang *et al*., 2003). Due to the shrinkage in lakes, less floodwater can be diverted from the main stream of Yangtze in flood season. Thus, flood stage at the Jianli sub-reach would rise to the warning stage in a shorter time (JALC, 1991). Moreover, riparian regions were also reclaimed by setting up levees, which greatly narrowed the river and raised water levels (Wang *et al*., 2003). For example, water stage in the 1998 flood at the Jianli station is higher than in the 1954 flood despite the lower water discharge during the 1998 flood (Li and Ni, 2001; Yin and Li, 2001).

7.2.2 Overbank sedimentation

DEMs indicate that about 5.0 × 10^7 m^3 of sediment deposited over the navigation reference plane from 1981 to 1997 (Table 6.2), which can be a credible indicator of the deposition during the over-bank flows from 1981 to 1997, including the large–magnitude flood in 1996. It was estimated that from 1966 to 1998, the lower Jingjiang reach consisting of the Shishou and Jianli sub-reaches received 1.8m of sedimentation. Particularly, siltation in the river channel can range from 0.6m to 1m thick, even 1.3 meters at Wuguizhou during the 1998 flood (Yin *et al*., 2004).

Fine-grained sediment suspended within overbank flows deposit on the floodplain due to reduction of flow velocity and increasing of flow width caused by channel overtopping (Brakenridge, 1988). Normally the flow velocity on the floodplain will decrease against the distance from riverbank; flow velocity over the flood plain is much lower than it in the channel and usually lower than the entrainment velocity (Knighton, 1998). Thus, sediments on the flood plain can be accumulated over time.

Inundation is the only means for river to accumulate sedimentation over riverbank, but the rate of overbank deposition depends on the frequency of inundating flows and their sediment load (Knighton, 1998). As it is mention in Chapter 3 (Study area), beside from the extreme flood events with low frequency such as 1954 flood and 1998 flood, the lower Jingjiang reach (including the Jianli sub-reach) attacked by the overbank flows almost every year (Shi *et al*, 1985). These bank-full discharges are envisaged as the main source of overbank sedimentation in this study. It has been long recognized that the dominant discharge, which occurs every 1-2 years did most geomorphic work (Wolman and Miller, 1960). Furthermore, the higher water level (Table 7.1 and Figure 7.3) and longer duration of overbank flow (see Chapter 3) enhances the sedimentation over riverbanks. Sediments over bank can be only transported and deposited within overbank flows.

7.2.3 Undercutting in the riverbed

Undercutting in the riverbed was represented in the longitude profiles extracted from the two DEMs in 1981 and 1997 (Figure 6.4). The lowest elevation in the 1997 longitude profile is lower than it in the 1981 longitude profile (See Figure 6.4). These are a credible indication of undercutting in the river channel of the middle Yangtze Reach. Meanwhile, cross-sections derived from DEMs (Figure 6.5) and cross-sections based on survey data (Figure 5.4 and 5.6) also revealed that undercutting in the riverbed occurred in most of the transections along the study reach. This can be corresponding with the others' result. Although Yin *et al*. (2004) did not point out the incision in the riverbed of the middle Yangtze River in their paper, the cross-sections they derived from the river channel topography maps have delivered the information of thalweg scouring although deposition can be observed on the bars or riverbanks. Pan and Lu (1999) and Tang (1999) compared the cross-section geometry along Jingjiang reach in 1965 and 1993 and have found that the whole lower Jingjiang reach was in an erosional status both in drought and flood seasons from 1965 to 1993.

The effectiveness of overbank flow depends not only on the amount of sediment they transported, but also on their ability to modify the river channel valley (Wolman and Gerson, 1978). On one hand, the increasing in velocity and shear stress in high stage events has greatly enhanced sediment transport capability, on the other hand, floodwater with higher velocity exerts larger shear stress on the riverbank and riverbed, and therefore riverbed scouring is strengthened by turbulent flow in the meandering river during wet seasons.

Undercutting in the riverbed is also determined by the composition of riverbed. The riverbed material in the Jingjiang Reach is very susceptible, which facilitates the scouring in the riverbed. According to You (1986), in the Jingjiang reach, rolling bedload (1.29Ø) accounts for 0.35%, saltating bedload (1.29Ø-3.35Ø) is dominant composition in the sediment load with overwhelming percentage (93.35%), and the percentage of suspended load (3.56Ø) is only 6.30%. Great percentages of saltating bedload and silt compostion in the riverbed of the Jingjiang reach make the riverbed susceptible to the great conveyance of flood, which entrains these materials with the secondary flow in the channel.

7.3 Impact of large floods

Aside from bankful discharge of 1-2 years return time, large floods with great magnitude have occurred more and more frequently in the Yangtze basin.

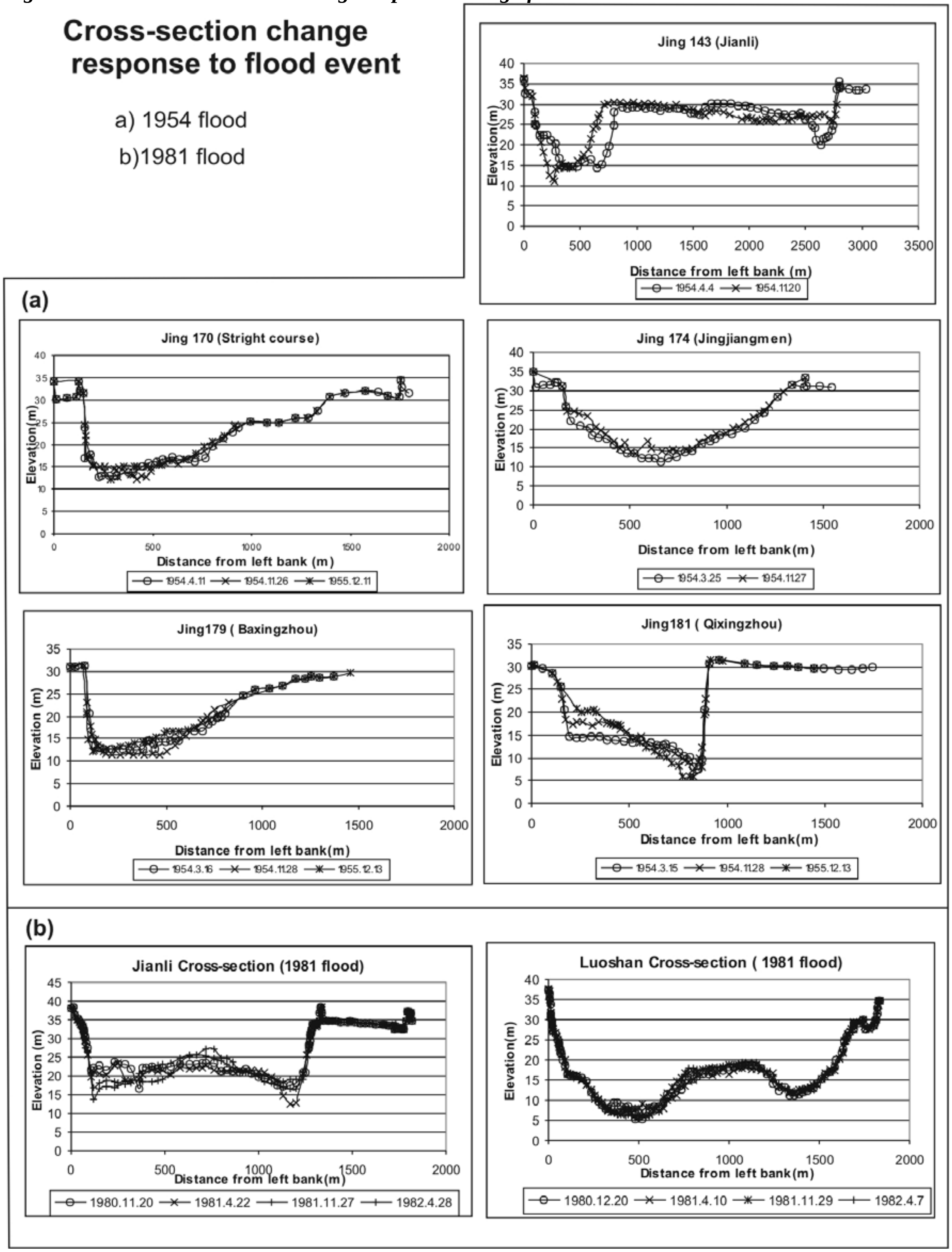
Understanding the impact of large flood has been of great importance for the Yangtze River management. Thus this study particularly tried to examine the impact of large flood in the middle Yangtze River. Due to the shortage of dataset, this study can only set floods in 1954 and 1981 as an example to examine the impact of large flood on river channel. The process and magnitude of these floods have been described in Chapter 3 (Study area).

Five cross-sections along the Jianli sub-reach (Figure 7.4 a) were selected for examining the impact of 1954 flood, and two cross-sections (Figure 7.4 b) for 1981 flood. Pre-flood channel cross-sections and post-flood channel cross-sections were compared in Figure 7.4. It can be seen that the 1954 flood promoted the development of mid-channel bar that Jing143 cross-section crossed (Figure 7.4a). Silation in the right channel was also very obvious in Jing143 cross-section (Figure7.4a). The cross-sections (Jing170 and Jing174) at the straight course remained a stable channel during flood time. Erosion and deposition co-existed in cross-sections (Jing179 and Jing181) along meander loops. The 1954 flood scoured the riverbed at Jing179, but deposition occurred in the following year and the channel tended to retrieve the status before the 1954 flood. In the cross-section of Jing181, deposition appeared at the inner bank (north bank), while erosion at the toe of the outer bank (south bank) in 1954 (Figure 7.4a). Similarly, in 1981 flood, the cross-section at Jianli (Figure 7.4b) shows that deposition occurred over the mid-channel bar and right channel (in the right), where 1981 floodwater scoured the north channel (in the left). It is obvious that flood in 1981 did not have much effect on Luoshan cross-section geometry (Figure 7.4b). This may attribute to the diversion of the Dongting Lake and other tributaries in the Jingjiang reach, which alleviate the pressure of flood on the river channel downstream of Jingjiang reach. In general, extreme flood events with great magnitude and low occurrence put effect mainly on the meanders (especially with mid-channel bars) in the study reach, rarely on the straight course and Luoshan station. Undercutting and siltation both occurred in the channel during the flooding period, however, the modification in riverbed may vanish in the following years because of its low frequency.

Moreover, this type of large floods also contributes to the sedimentation over floodplain and bars in the channel, which is difficult to be removed again. Yin and Li (2004) has found out the 0.2-0.4m thick of sediment was deposited on the middle channel bar along the Jianli sub-reach during 1998 flood.

Unfortunately, because of shortage of hydrological data, the available peak discharge records do not include the greatest floods (the 1954 flood and the 1998 flood) in the last 50 years. Hence the FFMI, which is used as a useful predictor in the likelihood of streams to experience major geomorphic change during large floods (Beard, 1975; Kochel, 1998; Kale, 2003), is not feasible for this study.

Figure 7.4 Cross-section change response to large flood events.



7.4 Effect of flood control measurements along the Jianli sub-reach

In the 1950s, YWCC put forward a three-phase improvement proposal to improve flood prevention (Hong, 1993):

1) to strengthen embankments including Jingjiang levee and Yangtze major levee;
2) to create retention area in the plains and lake district to halt flood water overflowing the levees;
3) to build up dams in the upper stream for flood regulation and power generation.

Apart from changes in hydrologic characteristics, human activities like these flood control measurements also influenced the natural channel evolution of the Jianli sub-reach, as they directly or indirectly altered channel geometry.

7.4.1 Effect of bank revetment

Bank protection structures along meandering river had an effect on the channel morphology and dynamics, through restricting the width of the wandering belt (Xu, 1997). From 1949 onwards, bank revetment has been carried out at the susceptible meanders such as the Jianli bend, Shangchewan bend and Guanyinzhou bend. The traditional bank revetment approach along the middle Yangtze River used boulders and lumber to strengthen the delicate riverbank at meander bends, which has effectively protected the fragile bank from further erosion. The decline of collapsed bank from 1981 to 1997 is a good indication of the success of such a method (Figure 6.3b).

However, it also has its negative effect on river channel changes. As it is mentioned before, all these revetment materials sink into the river channel, the channel capacity will be reduced and hydraulic geometry downstream will be affected (Simon, 1992). In addition, bank revetment will enhance the undercutting in the riverbed, because less sediment is entrained in the water flow and less energy will be consumed during the friction with riverbank (Winterbottom, 2000; Rinaldi, 2003). More stress will be added on the riverbed, which is more vulnerable than the protected riverbank. This may help explain the scouring in river channel in the Jianli sub-reach.

7.4.2 Effect of cutoff projects

As it is known that meanders are more susceptible than the straight course, the lower Jingjiang has the most varied cross-section along the middle Yangtze River, which can be related to its sinuous meanders (Figure 5.2). Similarly along the Jianli sub-reach, the Yanchuantao straight course is more stable than the meanders in the end of the Jianli sub-reach (Figure 5.6, 6.5). This is because that helicoidal flow in the meander scour the outer banks and deposit sediment on the inner bank, until the meander become the ox lakes.

As these meanders wind the navigation route and damp draining of floodwater, artificial cutoff is commonly implemented in meandering river to improve navigation and flood control in the world. The Shangchewan cutoff event has shortened river course by 29km (Figure 6.1). The cutoff project opened a new cannel for discharging water flow straightly. After implementation of artificial cutoff projects, the channel evolution was accelerated, followed by head erosion and undercutting (Figure 5.4). The riverbed and riverbank near the cutoff meander tend to be eroded during the adjusting period.

One of the consequences of the cutoff project in the lower Jingjiang reach is the severer bank erosion along the river (Figure 6.3b). This can be supported with the historical records, until 1991, the total length of collapsed bank along the Jianli sub-reach was 18.6km, taking up 14.8% of the reach length before artificial cut-off events in the later 1960s and early 1970s (JLAC, 1991). These bank collapses mainly occurred at/near meanders such as Jianli bend. After the Shangchewan cutoff event, bank collapse not only occurred at the meandering bends but also at the straight portion such as the Yanchuangtao course and the new cannel of the Shangchewan cutoff. In 1982, the collapsed bank immediately downstream of new cannel was 2.7 km long, while in 1985, the length of collapsed bank increased to 4 km (JLAC, 1991). The bank failure material and the bed material entrained from the new cannel were transported downstream and benefited the development of bars (Figure 6.3a). The river channel downstream and upstream of the abandoned bend will be subject to erosion (Figure 5.4).

Moreover, the Shangchewan cutoff event promoted the retention of high flood stage in the Jianli sub-reach (Table 3.7). This can be explained with the retention at the junction between Dongting Lake and Yangtze main stem. Cutoffs in the lower Jingjiang reach shortened the river course and reduced the ability of Yangtze main stem to discharge floods in time. The floodwater from upper Jiangjiang reach encounters the outflow flux from Dongting Lake and retains high flood level in the lower Jiangjiang reach for a longer time. Compared to the Shashi station upstream of the cut-off sites, the Jianli station suffered a longer warning time of extremely high water level in the flood events after cut-off events (JLAC, 1991)

7.4.3 Effect of levee construction

Now, the middle Yangtze riverbank is fortified by 30,000km of levees (Wu, 2003), these levees were raised up on the basis of the historical earth levee, which has a very bad foundation with high permeability. These historical levees can only withstand a 10-20 year recovery flood, overtopping occurred in the large flood such as flood in 1954 and 1998 (Plate 5). With the development of economy in the levee-protected area, a higher degree of protection may be desirable and justified, therefore levees along the middle Yangtze River have been consecutively reinforced in the past 50 years (refer to Chapter 3). Analysis on the navigation charts depicted that the length of major levee along both banks increased 32.7km, while the length of minor levee reduced 21.4 km from 1981 to 1997(Figure 7.5). Many minor levees were strengthened and upgraded as Changjiang major levee like those along new cannel of Shangchewan bend and Yanchuantao straight course (Figure.7.5). In particular, more money and human labour were spent on levee reinforcement after each catastrophic flood events. After 1998, P.R.China has spent billions on the levee reinforcement (Chapter 3). Levees along the river were raised up to 1-2 m higher (Li *et al.*, 2003).

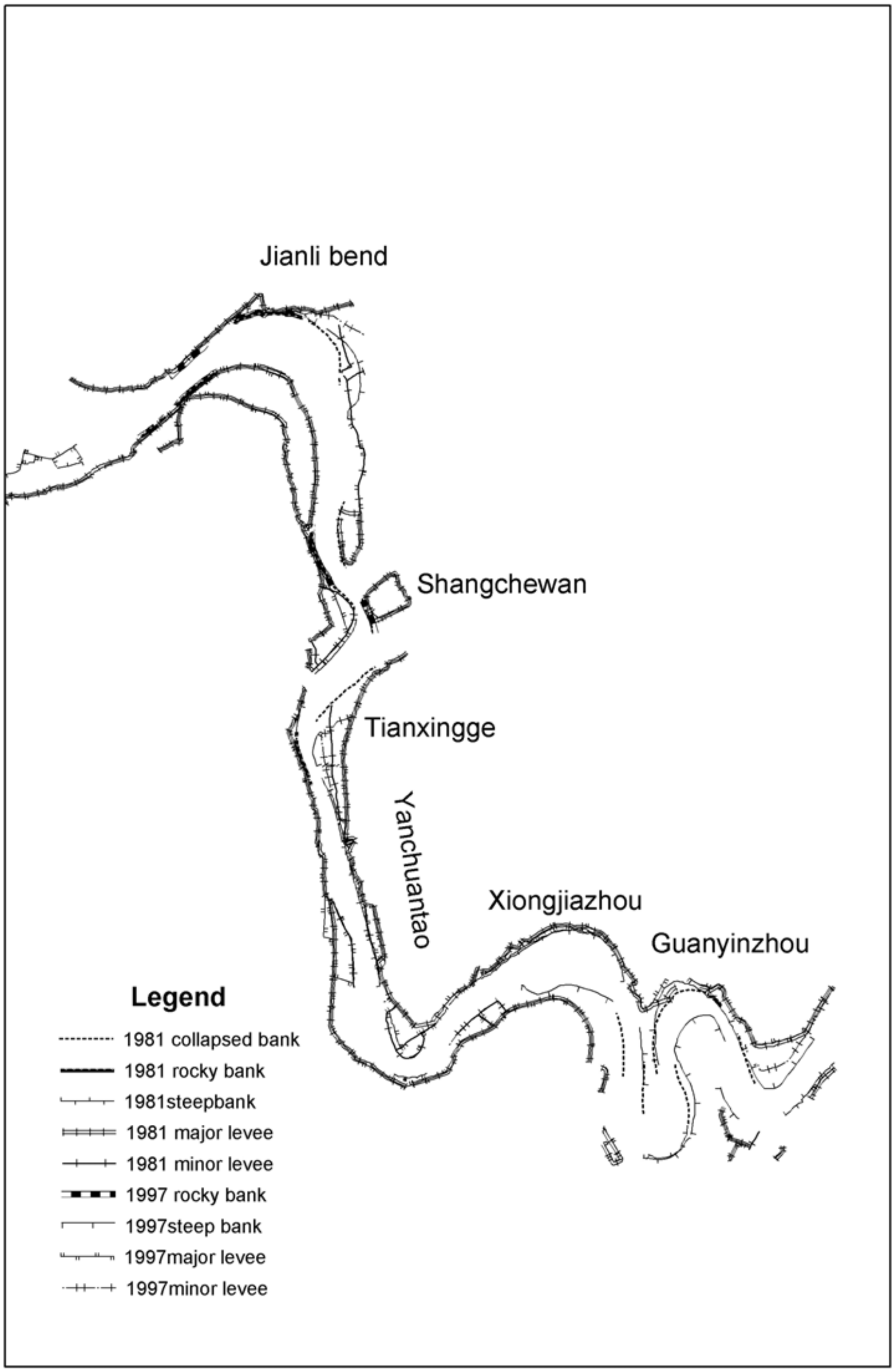
Plates 5 Overtopping of levee during flood in 1998.

This study believes that the extensive levee construction is the major contributing factor for the pattern of “overbank deposition, in-channel erosion” in the study reach, although public paid more attention on its flood prevention function. As a long existing feature along the middle Yangtze River, these two huge walls along both banks not only prevent the violent floods since several hundred years ago, but also work on the river channel evolution. As the study reach was almost completely controlled by the Yangtze major levee and local minor levees (Figure 7.5), the effect of overbank events would be amplified by the levee construction on the riverbanks, because overbank flow with high concentrated suspended sediment will be constrained into a certain area, which raises water stage and benefits deposition over banks and scouring in the channel during flooding time. Moreover after the Shangchewan cutoff event, flood flow cannot flush down immediately because of retention at Chenglingji, hence the flow entrained with suspended sediment has longer retention time, which benefits the sedimentation over flood plain (Yin and Li, 2001). Thus, the levee on the banks plays an important role in channel change pattern of "overbank deposition, in-channel erosion".

As levees became higher and higher, some new problems emerged, in regard to channel stability, flood duration and the levee security. Levee construction itself tends to result in increasingly higher flood stages and longer flood durations (Starosolszky, 1994). Chen and Lu (2003) found that the peak flood discharge along the lower Yangtze increased with the improvement of the flood control system (levee construction) of main stem and tributaries. Moreover, bank collapse pushed the water edge closer to the levees along the middle Yangtze River (Figure 6.3, 7.5).

Furthermore, deposition over riverbanks and constraint of levees strengthened the difference between the flood level within levees and ground elevation beyond levees. According to Zhou (1986), the flood level in Jingjiang river channel during 1998 flood is 16m higher than the elevation of Jingbei (meaning north of Jingjiang) flood plain behind the Great Jingjiang Levee. Besides, islands and bars in the channel of the Jingjiang reach are also 2-6m higher than the land behind the levees (Yin *et al.*, 2004). If any levee failure happened in the middle Yangtze River, huge flood wave with more than 10 m water head would sweep the prosperous middle Yangtze basin and affect more than 5 million citizens living in the area (Zhang *et al.*, 2000).

Figure7.5 Levee construction and bank erosion in the Jianli sub-reach from 1981 to 1997.



I am not suggesting that levee construction along the meandering middle Yangtze Rive does not help prevent flood, but there is convincing evidence that reinforcement on the historical levee may not alleviate the magnitude of flood hazard. As people took the safety of new levee for granted and developed their life in levee vicinities, any leakage along the levee may cause a devastating levee collapse. In this meaning, the higher levees cannot solve the problem of flood but may cause greater loss.

Most importantly, different from other human activities that temporarily disturb the balance between channel geometry and hydrology regime, levee construction has its long-term effect on river channel change until it is removed by floodwater or human one day. Therefore, more consideration shall be taken when planning levee construction on the rivers.

7.5 Conclusion

This chapter has probed into the empirical reasons of channel change happened in the last 50 years. Basically the changes were attributed to hydrologic regime change and human disturbance. Dongting shrinkage resulted from lake reclamation induced the greater water discharge and sediment load in Yangtze mainstream (the Jianli sub-reach) and higher frequency of bankful discharges with higher water stage and longer duration. These initiated severe bank erosion, channel undercutting and overbank deposition.

Particularly, the impact of large flood was examined by comparing the cross-sections. Results suggest the large flood did not put much effect on the river channel change but did contribute to the overbank sedimentation. After examining the impact of each types of human activities along study reach, we believe that the “overbank deposition, in-channel erosion” pattern is more related with the severe levee construction and bank revetment, which benefit overbank deposition but cause higher water stage through confining water flow into the certain area during flood seasons.

Chapter 8. CONCLUSION

8.1 Overview of this study

Historical channel change along the Jianli sub-reach since 1949 has been reconstructed on the basis of hydrologic survey data and map sources. Historical hydrologic survey data (before 1987) along the Jingjiang reach has been employed to examine the changes in 20 cross-sections (including 5 cross-sections at major stations along the middle Yangtze River and 15 cross-sections along the Jianli sub-reach). Two series of map sources (channel distribution map and navigation charts) are used to evaluate the planform change, cross-section change and volume changes along the Jianli sub-reach after 1981. Given the existence of levees on the banks, the study reach did not experience major channel pattern change, but channel widening and severe bank collapse have been observed. Cross-sections derived both from hydrological survey data and DEMs constructed from navigation charts have shown an "overbank deposition, in-channel erosion" pattern along the study reach. This is in accordance with the calculation of erosion/deposition volume from DEMs. The erosion volume is larger than the deposition volume, and erosion/deposition areas are mainly at meanders. After examining the hydrologic regime changes during the last 50 years and the impact of intense human activities in the Jianli sub-reach, the following conclusions can be drawn from the analysis of river channel change on the Jianli sub-reach.

1) Hydrological regime change resulting from lake shrinkage has substantially affected river channel change over the last 5 decades. Increased water discharge and sediment load in the main stem of the Jingjiang Reach enhanced bank collapse and bank migration along the study reach, which result in minor channel widening with the constraint of levees. Intensive overbank discharge facilitated sedimentation over the riverbank, and higher water level promoted the undercutting in the riverbed.

2) Comparison between pre-flood and post-flood cross-sections indicated that extreme floods with low frequency like the floods in 1954 and 1981 did not have much effect on the river channel geomorphology, as it was observed that the river channel retrieved its balance in riverbed sometime after the occurrence of flood. But the higher stage and longer duration of large floods promoted sedimentation over floodplain and incision in the riverbed.

3) Flood control measurements have had their negative effect on river channel change in the study reach as they disturbed the natural evolution of the river channel. Bank revetment reduced the channel capacity but provided sediment source for bar development. Cutoff projects shortened the river length and exacerbated erosion near the cutoff meander. Besides the impact of bank revetment and artificial cutoff, the impact of levee construction on channel change has been emphasized in this study. Because levees along the banks control the spread of floodwater, they cause higher flood stage and prolong flood duration, and further promote the sedimentation over the

floodplain and undercutting in the riverbed. Most importantly, as a permanent feature on the riverbank, levees will have its long-term impact on the river channel evolution.

8.2 Achievements and their implications

With the help of GIS technique, large scale navigation charts were employed in this study to simulated river channel changes in the Jianli sub-reach under the constraint of levees on banks. This provided a new and economical approach to study river channel changes along the Yangtze River, on which field survey for research is difficult and expensive.

This study has identified the location and volume of erosion and deposition in the river channel, which is very helpful for better estimating river channel changes after the closure of TGD in the future.

In addition, this study has examined the impact of floods of different magnitude on river channel change, which is important for guiding flood-prevention work in the middle Yangtze River.

Furthermore, this study has emphasized the effect of levee construction on river channel evolution which has been long neglected by river engineers along the Yangtze River.

The results can be an important reference when deciding on river management related to the large Yangtze River.

8.3 Limitations

Although this study have achieved to detect the major channel changes along the study reach and have elaborated on the role of hydrological regime change and human activities on the erosion/deposition pattern in the Jianli sub-reach, there are some limitations in this study, which would affect the accuracy of the result and discussion.

1) Due to the discontinuous dataset, this study cannot present a comprehensive channel change on the basis of one consistent type of data. This would affect the accuracy of result when discussing the consecutive channel change in last 50 years.

2) Instead of on-site surveying cross-sections along the study reach, this study used DEMs to simulate the cross-sections from 1981 to 1997. The accuracy of the elevation in the cross-section is determined by the resolution of contours in the navigation charts, which cause a deviation between simulated elevation data and real-world elevation data.

3) Furthermore, although some major river channel changes along the study reach have been detected, the uncertainties remain due to employment of the small-scale maps (channel distribution map).

8.4 Prospects and further study

River channel change is a function of several controlling factors, such as alteration in hydrologic regime, disturbance of human activities. In this study, hydrologic regime changes are close related with human activities in the river basin. Although this study has probed into the impact of human intervention, it is still very difficult to quantify the impact of each human activity. To better understand the impact of each human intervention, on-site field survey on flow regime and sediment (including suspended sediment and bedload) analysis will be necessary.

Besides, if peak discharge over a longer period can be observed, it would be clearer which discharge is more responsible for the geomorphology changes in the channel along the middle Yangtze River by calculating Flash Flood Magnitude Index (FFMI). Similarly, when the large scale navigation charts for a longer time period is available, the estimation for future channel change would be more accurate.

There is growing concern about the river channel change after the completion of TGP in 2008, as the hydrology regime in the middle and lower Yangtze River will be greatly changed. Many studies have been published to predict the downstream channel change after TGP completion (Fang, 1993; Qian et al, 1994; Yang et al, 1998). The common understanding is that the Jingjiang reach would endure erosion status for at least 50 years after the closure of TGD. Practical experience from the other large dams in the world like the Hoover Dam in Colorado River show that significant degradation and bank erosion would occur in the first 100 years (Leopold, 1996). Current riverbank in the lower Jingjiang reach is very close to the levees, further bank erosion may cause the Jingjiang levee in jeopardy. Therefore, more effort should be taken to identify river channel changes (particularly bank migration) along the Lower Jiangjiang reach under the new hydrology regime, especially after the completion of TGP.

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