# Flood management in the lower reach of the Yellow River

TU Delft

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# PREFACE

This research was part of a co-operation between research institutes and universities in China and the Netherlands. Within this co-operation I was given the possibility to investigate the Yellow River, in particular the flood control problems of the lower reach of the Yellow River. The results are described in this report. I would like to thank all participants in this co-operation for their involvement.

I would like to thank my supervisors from Delft University of Technology. Prof. de Vriend, Prof. van Beek and Dr. Wang, for giving me the opportunity to carry out this research and for their support and assistance during the research period.

I would like to thank the Yellow River Conservancy Commission in China and in special mrs. Liu Xiaoyan and mrs. Sun Feng for their co-operation and for providing the facilities during my stay in China. Without their hospitality and their understanding this research would have been impossible. I would like to thank mr. Zhang Yuanfeng and mrs. Liu Hailing for their patience to teach me more about the Chinese culture and the complexity of the Yellow River. Their help, their understanding and the interesting discussions we had, made an indescribable contribution to this research but also to my understanding of China and its culture.

Last but not least I would like to thank my friends Femke Griffioen, Alain Maas, Rafael Tamsiran and Michèl de Vaan for their willingness to read and correct the concept versions of this report. Their ideas and recommendations were very important for the realisation of this work.

Erik Kemink

Delft, May 2002

# SUMMARY

Due to a combination of factors the risk of flooding is increasing significantly in the lower Yellow River. Moreover more and more people settle in the flood plains and the areas prone to flooding. The risk of a large number of casualties becomes serious and the potential damage is high. The Yellow River Conservancy Commission (YRCC) decided to construct the Xiaolangdi dam to face the flood control problems. The Netherlands also faces flood control problems and had to search for new measures to guarantee the safety of the people living in the flood prone areas. The possibility of learning of the "Room for the River" policy in order to improve the flood control of the lower Yellow River is investigated in this study.

The study is carried out in co-operation with the YRCC, within the framework of a project between a number of research institutes and universities in China and the Netherlands. The necessary data of the study are supplied by the YRCC. The data analysis was carried out in China during the summer of 2001, whereas the modelling work and the evaluation of the measures have been carried out in the Netherlands.

For the evaluation of measures it is necessary to analyse their impact to the water levels, discharges as well as the morphology of the river. For this purpose an one-dimensional model for the lower Yellow River has been set-up, based on the 1D modelling software package SOBEK of WL | Delft Hydraulics. The model simulates the flow, sediment transport and morphological development from Tiexie to Gaocun, a reach of 300 km of the lower Yellow River.

The definition of preferable measures to improve the flood control in the lower Yellow River is based on the Dutch "Room for the River" policy. Before the measures are defined the base case is analysed and the possibility to adapt the "Room for the River" policy for the lower Yellow River is investigated. The criteria to figure out the usefulness of a measure are the influence of the measure on the water motion and the morphological response of the river. There are differences in the effect between the measures, but all have in common that they lower the water level during a flood with respect to the base case.

Based on the results of the evaluation of the measures four strategies have been developed by combining the various measures. All the strategies met the most important objective, i.e. to improve the safety of the lower Yellow River. The strategies show that there are a lot of possibilities to improve flood control. The screening of the impact of the strategies have put forward that one of the bottlenecks for the implementation is the number of people living on the flood plains and in the detention basin.

Due to the limited scope of the present study and restrictions of data availability and the reliability of the used model, the results of the study should be considered as indicative, rather than quantitative. Nevertheless the study has shown that the conceptual approach as applied in the Netherlands for the flood control of rivers, can certainly be useful for the flood control of the lower Yellow River.

## About the author

The author is a student at Faculty of Civil Engineering of Delft University of Technology in the Netherlands; supervised by the Department of Hydraulic Engineering and the Department of Watermanagement. This report is written for his M.Sc.-thesis within the framework of a co-operation project between a number of research institutes and universities in China and the Netherlands. The objective of this co-operation is to strengthen education and applied research in the following areas: Integrated Water Resources Management, Flood Control, Dike Construction, Hydrodynamics, Dredging and Environmental and Ecological Aspects of Water Management. This thesis is executed within this co-operational framework and is related to the topics Integrated Water Resources Management and Flood Control. The first part of this study has been carried out at the Research Institute of the YRCC in Zhengzhou, China.

## Currency equivalents (May 2002)

| | | |
|---|---|---|
| Currency Unit | | RMB (Yuan) |
| Y1.00 | = | $0.1208 |
| $1.00 | = | Y8.2767 |

## List of abbreviations

| | |
|---|---|
| AC | After Christ |
| ADB | Asian Development Bank |
| AIS | Administrative- and Institutional System |
| BC | Before Christ |
| DUT | Delft University of Technology, the Netherlands |
| GDP | Gross Domestic Product |
| IWRM | Integrated Water Resources Management |
| LYR | Yellow River lower reach |
| MWR | Ministry of Water Resources |
| NPV | Net Present Value |
| NRS | Natural Resources System |
| PRC | People's Republic of China |
| RMB | Chinese monetary unit |
| SES | Socio-Economic System |
| WB | World Bank |
| WL | WL\|Delft Hydraulics, the Netherlands |
| WRM | Water Resources Management |
| WRP | Water Resources Planning |
| WRS | Water Resources System |
| YRB | Yellow River Basin |
| YRCC | Yellow River Conservancy Commission, Zhengzhou, China |

## Weight and measures

| | |
|---|---|
| ha (hectare) | 10,000 $m^2$ |
| kg (kilogram) | 1,000 grams |
| km (kilometre) | 1,000 m |
| $km^2$ (square kilometre) | 100 ha |
| m | meter |
| $m^2$ | square meter |
| $m^3$ (cubic meter) | 1,000 litres |
| s | second |

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# 1 INTRODUCTION

## 1.1 PROJECT DESCRIPTION

### 1.1.1 CHINA

China is situated in eastern Asia, bounded by the Pacific in the east. It has an area of 9.6 million $km^2$, or one-fifteenth of the world's land mass(1). The total population is 1,2591 billion (1999). This is about 22% of the total population in the world. The national average density of population is 119 per $km^2$ (1990) (2).


Figure 1: Map of China

Figure 2: Location Yellow River Basin in China

Despite strict measures from the government to slow down fertility rates, China's present population still continues to grow. By the year 2050 it will reach about 1.5 to 1.6 billion, according to most Chinese demographers and to the medium variant of UN projections. This massive population increase will mainly strike eastern China, including the Yellow River basin's lower reach, an area which is already extremely densely populated, and at the same time, intensively cultivated (Fischer et al, 1999). The economic growth rate in China between 1995 and 2000 was on average 8.6%(1). China has 50,000 rivers with a catchment area of more than 100 $km^2$, of which 1,500 have a catchment area exceeding 1,000 $km^2$. Most of these rivers flow from west to east to debouch into the Pacific Ocean. Main rivers include the Yangtze, Yellow, Heilong, Pearl, Liaohe, Haihe, Qiangtang and Lancang(1).

### 1.1.2 GENERAL FLOOD CONDITIONS IN CHINA

The following section is based upon NEDECO - WL| Delft Hydraulics, 2001. *Flood management study of Hai River.* § 1.2.1

Floods are the most devastating components of China's water problems. The heavy flood disasters that have occurred are mainly caused by the monsoon climate, characterised with uneven rainfall distribution and the existing natural and geographic conditions in China. Monsoon rainstorms can bring more than a meter of rain in a 24-hour period, resulting in quickly swelling streams and rivers. Despite centuries of efforts in constructing dams to hold back flood water and dikes to keep water within their banks, devastating floods occur almost yearly somewhere in China. Floods on average inundate several million hectares, and cause about 200 billion RMB in direct economic losses each year on average basis. A serious contributing factor in making even "normal" floods more destructive seems to be the deteriorating morphology of riverbeds, particularly in the Northern China. Increased diversions of water for consumptive uses and resulting siltation have sharply reduced the sediment transport capacity of the rivers. This increases the probability that a certain flood discharge will overtop or breach a dike.

A combination of factors led floods to cause far more economic and social damage than in the past. Economic growth is often concentrated along the major rivers. Which means that there is far more valuable infrastructure at risk with each passing year. Extreme population and land pressure have forced millions to live and farm on flood plains. Some of the flood detention areas are highly developed and are populated with millions of people. Furthermore, the visibility of large flood control works on the rivers had led to a perception of increased safety and increased willingness to invest in housing and productive assets.

The population distribution in China is extremely uneven and the population density varies much between different areas. The regions prone to flood threats are often those with the highest population densities and a relatively well developed economy. The river plains in the middle and lower reach of the main river basins and coastal regions are the areas that have most frequently and severely been threatened by floods. These areas make up only 8% of the territory of the country but have 40% of the country's population, 35% of the cultivated land and 70% of the gross value of industrial output.

After centuries of flood-fighting efforts in China, floods continue to demand a heavier economic and social toll each year: with economic growth, there are more and more assets at risk for a given flood. The only statistically evident progress that has been made is saving lives through early warning and communication systems.

### 1.1.3 THE YELLOW RIVER BASIN

The Yellow River is the second longest river in China. The river got its name from the muddiness of its water, which bears a perennial ochre-yellow colour (3). The area of the Yellow River Basin is 795,000 $km^2$. and the length is 5,464 km. In 1990 a population of 97.81 million people was settled inside the basin, which is 8.6% of the total nation (YRCC, 1999). The Yellow River Basin is located between the dry area of north-west China and the wet area of south-east China. The river originates in the Yagmadagze Mountains in the Qinghai province. Here, at an altitude of approximately 5000 meters, precipitation gives rise to streams that join into a river –the Yellow River- at the foot of the Bayankala Mountains. From here the Yellow River flows eastward through eight provinces, Qinghai, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan and Shandong, before it debouches into the Bohai Sea (Fischer et al, 1999). According to the geographic, geological and hydrological conditions, the main stream of the Yellow River can be divided into the upper, middle and lower reach (Li, 2001).


Figure 3: The Yellow River flows through eight provinces

The upper reach is situated on the Tibetian plateau from the Yagmadagze Mountains to the city Hekouzhen. The middle reach is mainly located on the Loess plateau. The lower reach is situated on the alluvial plains in Henan and Shandong provinces (Fischer et al, 1999). Between the upper- and the middle Reach the interior basin is situated. This basin is hydrological independent of the Yellow River Basin (see the red part in Figure 4).

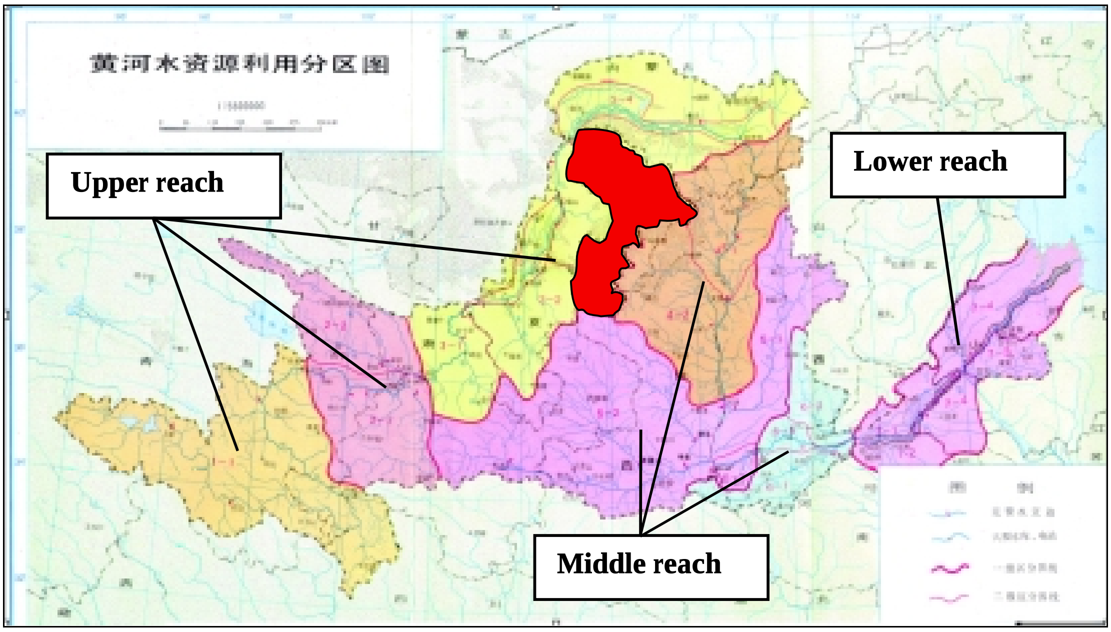


Figure 4: The upper, middle and lower reach

### 1.1.4 GENERAL FLOOD CONDITIONS IN THE YELLOW RIVER

The Yellow River has an important economic function for Northern-China. Around one hundred million Chinese depend on the Yellow River for water supply. At the same time the river and its basin face a lot of severe problems. As the most sediment-laden river of the world the extreme sediment load of the river causes problems in water resources management and flood protection (Li, 2001). One of the main problems of the lower reach of the Yellow River is the decreasing conveyance capacity. It is the result of the river being filled up by sediment and the absence of sufficient flow to maintain the necessary sediment transport capacity. The sediment of the river originates mainly from the middle region of the river's basin. During the July-September rain season, heavy rainfall erodes loess cliffs rapidly bringing a huge amount of eroded silt into the rivers and finally to the main channel (3). The areas in the lower reach are suffering from these problems and are also the most densely populated areas of the basin and the economically most-developed areas of the country. Therefore flood control is not only vital to these flood-prone areas but for the whole nation.

The governmental policy for the Yellow River since 1950 is to "retain water in the upper- and middle reach, drain water at the lower reach, and divert and detain water on both sides of the river", guided by the notion of "stabilising the flow by widening the channel" (Li, 1999). Before 1949, the river overflowed its banks twice every three years, thus earning the title "China's Sorrow". In contrast, the river has also been called the "Mother of China" for its central role in the early Chinese social and economic development. The symbol that these divergent metaphors fail to evoke is the one of water scarcity. In 17 out of the past 25 summers the Yellow River's bed has been left dry further and further upstream for longer periods of time (Zusman, 1998). The annual average runoff for the Yellow River is 58 billion $m^3$, only one seventh that of the Mekong River, which has a comparable catchment area (ADB, 2001).

The reach from Huayuankou to the Bohai Sea is a remarkable part of the Yellow River. It can hardly be seen as a basin and it is no longer a river, but a man-made channel surrounded by dikes to protect against flooding. This part of the river is also named the suspended river, because the riverbed is higher than the surrounding land. This is the reason why the area of the lower reach of the Yellow River basin is only 3% of the total basin whereas it's length is about 15% of the total.

### 1.1.5 PROJECT AREA

Originally it was planned to examine in this research the whole lower reach of the Yellow River, which is from Xiaolangdi to the river mouth. During the study it was decided to shorten the project area. Instead of the whole lower reach of the Yellow River only the wandering stretch from Xiaolangdi to Gaocun (310 km, see also Figure 5) is examined.

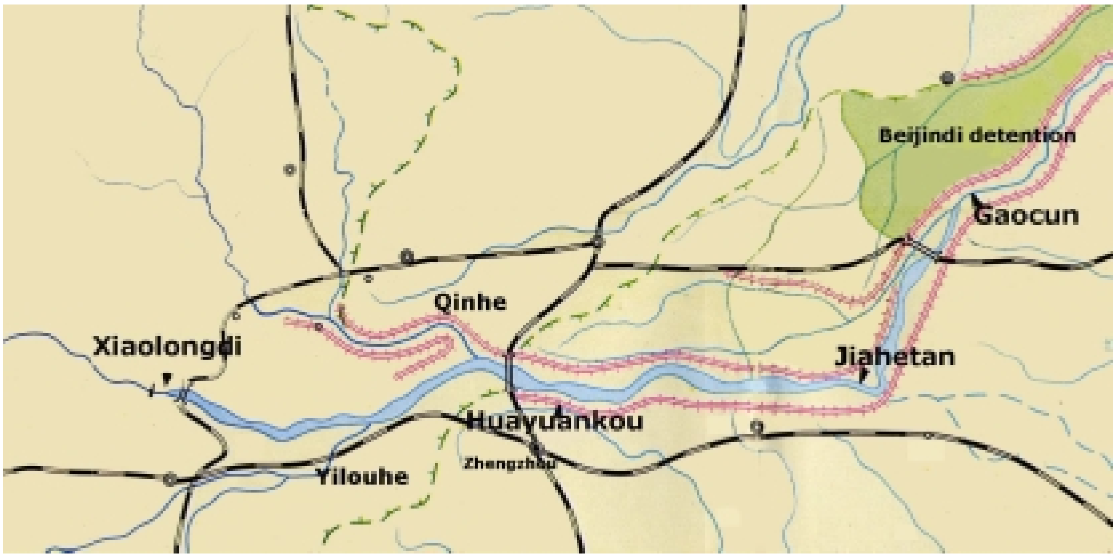


Figure 5: Map of the project area (Source: YRCC)

The first reason for shortening the study area is that, although the whole lower reach of the Yellow River faces flood control problems, the impact of a dike breach in this wandering stretch is more severe than for the rest of the lower reach. Most of the flood prone areas exist due to the threat of dike breaches in the section between Huayuankou and Gaocun. The second reason was that the counterpart, the Yellow River Conservancy Commission (YRCC), expected that the project time would be insufficient to study the whole lower reach of the Yellow River and therefore advised to focus on the section between Xiaolangdi and Gaocun. Xiaolangdi is taken as starting point because in that way the whole wandering stretch is incorporated in the project. Secondly this will increase the accuracy of the results at Huayuankou, which is important because the section between Huayuankou and Gaocun is the most important section in terms of flood control.

## 1.2 AIM OF THE STUDY

Due to a combination of factors, in particular the decreasing flood conveyance and the low design flood discharge, the risk of flooding is increasing seriously in the lower reach of the Yellow River. Moreover more and more people settle in the flood plains and the areas prone to flooding. This is mainly caused by the rapid population growth in the area. The risk of a large number of casualties has become very serious and, due to the economic development, the potential damage is high, especially in the lower reach. Therefore, reducing flood risk is an important concern for the governments and the communities responsible for the lower reach of the Yellow River. To improve flood control many different measures can be implemented to reduce the flood risk.

The YRCC decided to construct the Xiaolangdi dam as one of the measures to improve the flood control. This measure will lower the 1/1,000 flood peak to 22,500 $m^3s^{-1}$, and enables control without using the Beijindi detention basin (see Figure 5). However, due to the heavy sediment load, within about 15 years of operation the reservoir will be filled for 66% with sediment and the storage capacity of water will decrease from 12 to 4 billion $m^3$.

The Netherlands also faces flood control problems and is searching for new measures to guarantee the safety of the people living in the flood prone areas. This study will make use of the measures put forward in the new Dutch “Room for the River” policy. The challenge is to figure out the possibility to adapt the “Room for the River”-philosophy of the Netherlands to the lower reach of the Yellow River. This “Room for the River” policy will be compared with the situation before the construction of the Xiaolangdi dam.

This study intents to show how to set up a framework for water resources planning, in this case the flood control problems in the lower reach of the Yellow River, in order to improve the performance of the system. Due to the complexity of the problem, the restrictions in data availability and the restrictions in terms of the available knowledge to handle and solve this problem, it proved to be impossible to set up a detailed quantitative flood management study. Instead, the study focussed on the conceptual approach, i.e. how to carry out such studies. Hence the quantitative results of this study have only an indicative value. These indicative numbers and the experience gained from applying the approach forms the base for recommendations for further research.

**Based upon above the aim of this study has been formulated as:**
To study the flooding problems in the lower reach of the Yellow River and investigate how far the approach and measures as applied in the Dutch “Room for the River” policy can help in improving the flood control for the Yellow River between Xiaolangdi and Gaocun.

## 1.3 METHODOLOGY

The methodology for reaching the aim of this study is based on a policy analysis and more specifically the method of system analysis. Other approaches can also be useful but it is believed that system analysis provides the best basis for complex studies on the use of natural resources (Van Beek, 2000). The approach and how it is applied in this research project is explained in this section. System analysis is a method to unravel complex situations and is based upon the identification and analysis of a system and it's subsystems by giving a quantitative description of the interactions between these subsystems in terms of input-output relations and control variables. Within the context of a policy analysis it is essential to identify problems and goals from society with respect to the present and future performance of the system. Through changing the control variables, the functioning of the system is optimised with respect to the identified goals. The complexity of the Yellow River is asking for such a systematic approach and therefore a system analysis approach is used for this study. The description of the phases of this study, the activities in these phases and the interactions between activities is referred to as the analytical framework. The analytical framework for this study is shown in Figure 6. The three main phases of the framework are inception, development and selection.

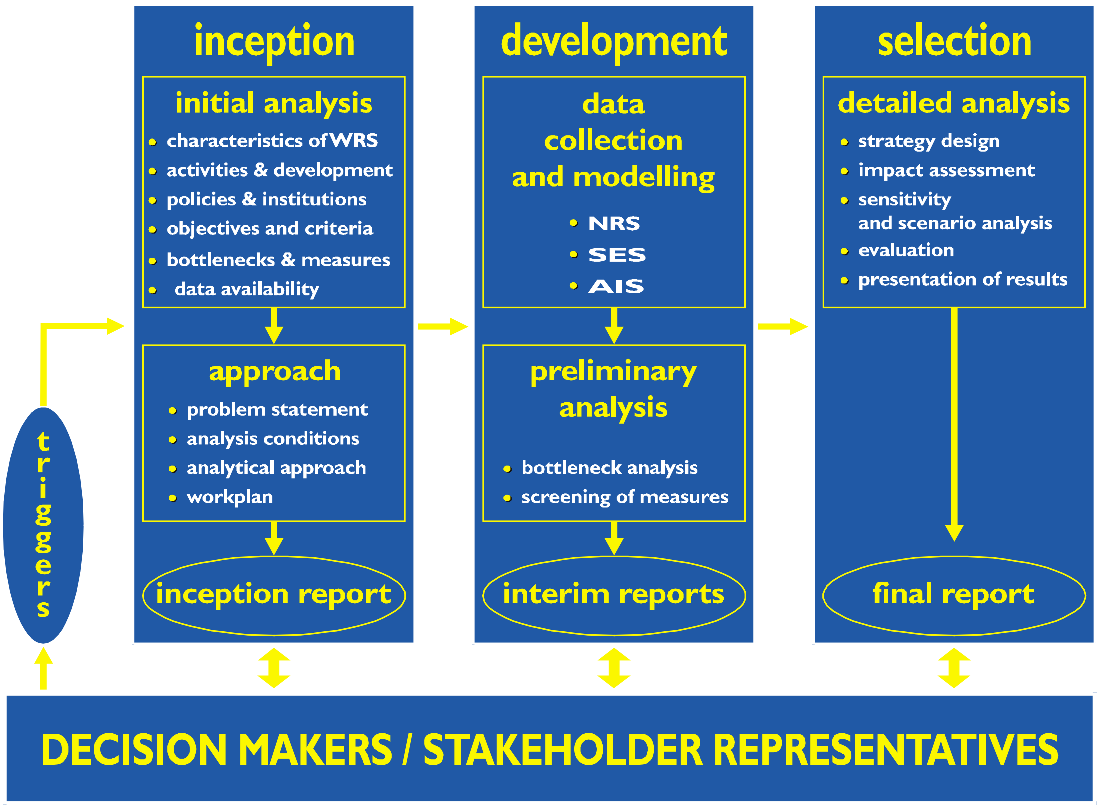


Figure 6: Analytical framework for WRP studies (Source: van Beek, 2000)

In the inception phase the subject of the analysis, the Yellow River, the problems and objectives are described. The development phase is divided in two sub-phases. First the data collection and the modelling and second the bottleneck analysis and the screening of the measures. In the development phase, the tools for the analysis and possible solutions are developed. The last phase, the selection phase, is to generate a limited number of strategies out of the promising measures and to assess their effects in terms of the evaluation criteria.

### 1.3.1 INCEPTION PHASE

The subject of analysis, the water resource system (WRS) of the Yellow River, is described to get a better insight in the interests and the conflicts in the system and especially the (conflicting) interests in terms of flood management. If one wants to optimise the functioning of the system, in this case the flood management of the Yellow River, one should know which functions are at stake, how these functions will be affected by the different development paths and which values can be assigned to these changes of functions. Identification of the relevant functions of the WRS of the Yellow River is thus the starting point for the analysis. Using systems analysis to describe this WRS, one can conceptualise the WRS as an input-output system. The inception phase, the problem analysis and the identification of the functions of the Yellow River, is described in chapter two.

### 1.3.2 DATA COLLECTION AND MODELLING

The data collection and screening was executed in China during the summer of 2001. All the data required to analyse the flood situation of the Yellow River in detail were not available or were available but only in a general format. The required and available data are described in section 3.2.

The objective of the modelling of the Yellow River between Xiaolangdi and Gaocun is to make an inventory of measures that can improve the flood control between Xiaolangdi and Gaocun. To determine the bottlenecks and the impacts of these measures on flood control it is useful to analyse the water levels, discharges, bed levels and the slope. For this the length scale along the river is the most important dimension. The other dimensions are less relevant to this study. That is the reason why a 1D-time dependent mathematical model is used. 1D means that one spatial dimension is considered, viz. the one along the river. Variations within the river cross-section are not taken into account, or only in a parametric way. Time-dependent means that time variations are modelled.

The available 1D-mathematical modelling system is the software package SOBEK. This package has been developed in the Netherlands by Delft Hydraulics. SOBEK is in concise technical terms a one-dimensional open-channel dynamic numerical modelling system, equipped with a user shell and capable of solving the equations that describe unsteady water flow, salt intrusion, sediment transport, morphology and water quality. For the Yellow River case the salt intrusion and water quality options have not been used. The description of the model set-up, including the reliability of the model, is described in chapter 3.

### 1.3.3 BOTTLENECK ANALYSIS AND SCREENING OF MEASURES

The second half of the development phase, the preliminary analysis, consists of the bottleneck analysis and the screening of the measures. This phase is described in chapter 4. The base case is developed with the 1D-model in combination with historical data about the elevation of the riverbed and the flood prone areas. The base case is used to determine the bottlenecks in terms of flood control.

The definition of preferable measures to improve the flood situation in the lower reach is based on the Dutch "Room for the River" policy. Comparing the Dutch situation with the Chinese situation checks the usefulness of the "Room for the River" policy for the Chinese conditions. The base case analysis and the results of the possibility to adapt the "Room for the River" policy are used as a starting point to come up with measures to improve the functioning of the system.

The evaluation of the measures is also carried out with the 1D-model. The criteria to figure out the usefulness of the measures are the influence of these measures on the water motion and the morphological river response. The promising measures show an improvement of the flood situation based on these criteria.

### 1.3.4 STRATEGY DESIGN AND IMPACT ASSESSMENT

The final activities in the systems analysis for water resource management (WRM) are to define strategies out of the promising measures and to evaluate these strategies. The results are described in chapter 5.

First of all the criteria are described. The selection of the criteria is based on their relation to the objective of the study. It is important that the criteria are comprehensive and measurable. One of them is safety and that one is checked with the help of the 1D-model.

The second step is the definition of strategies, which is based on a combination of promising measures out of the previous phase. The overall objective is to define strategies that fulfil the objective for this study as good as possible. Furthermore it is possible to define themes and to define strategies based on these themes. The usefulness of the strategies is screened with the criteria defined above.

The third step is the impact assessment. During this step the strategies are compared. The comparison is based on their scores with respect to the evaluation criteria. There are many ways to present the results. For this study the results are presented in a scorecard. This method allows the decision-maker to assign himself the appropriate weight to the criteria.

# 2 DESCRIPTION OF THE YELLOW RIVER AND PROBLEM ANALYSIS

This chapter describes the first phase, the inception, of the analytical framework, see also Figure 7. The functioning of the Water Resources System of the lower reach of the Yellow River is described within the concept of Integrated Water Resources Management (IWRM). The outcome of the first part of this chapter is a framework of IWRM with special attention for the position of flood control in the lower reach of the Yellow River. One should understand that the way the concept of IWRM is adapted to the Yellow River in this chapter is only rough and quick. It can only be used to show the main ideas and to show the need of the concept of IWRM to improve flood control. For a better and a more detailed study on IWRM in the Yellow River Basin reference is made to the Ph.D.-study of Li Rongchao (Li, 2001).

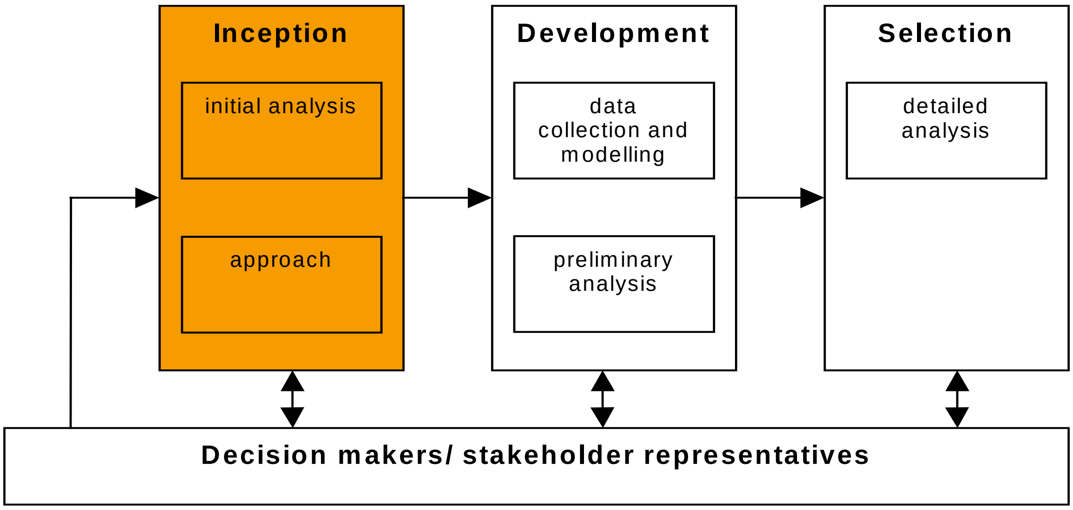


Figure 7: First phase of analytical framework

To adopt the concept of IWRM it would be better to look at the whole basin instead of a part of it, because all parts interact with each other and cannot be seen as autonomous. Still it is possible to apply the concept to a part of the basin, i.e. the lower reach of the basin. But one should keep in mind that there are a few restrictions.

In order to set up the framework of IWRM first the different components of the WRS are described. The problem is that most data provide information about the whole basin and not only about the lower reach. In these cases the data of the whole basin have been used because these data at least give an idea of the values for the lower reach of the Yellow River. The last section of this chapter is a kind of brief summary that can also be seen as the problem statement. The summary provides the main conflicts in the WRS as described in sections 2.2 to 2.4.

## 2.1 THE CONCEPT OF IWRM

The world's and also the Yellow River's water resources are under increasing pressure. Growth in population, increased economic activity and improved standards of living lead to increased competition for and conflicts over the limited water resources. Pollution of water is inherently connected with human activities, especially in the lower reach of the Yellow River. The Yellow

River acts as a sink and transport mechanism for domestic, agricultural and industrial waste causing pollution. Lack of pollution control measures further degrades the water resources.

The above problems are aggravated by shortcomings in the management of water. Sectoral approaches to water resources management have dominated in the last decades and are still prevailing; this leads to the fragmented and uncoordinated development and management of the water resources. Moreover, water management is usually left to top-down institutions, the legitimacy and effectiveness of which have increasingly been questioned. So the overall problem is caused both by inefficient governance and increased competition of the finite resource (Global Water Partnership, 2000).

To face these conflicts and to find solutions the concept of IWRM has been developed. IWRM is a concept that can be used in many situations and conflicts. The following definition of IWRM (Global Water Partnership, 2000) is used to provide a common framework:

**IWRM is a process, which promotes the co-ordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.**

The concept of IWRM –in contrast to traditional, fragmented water resources management- at its most fundamental level is as concerned with the management of water demands as with its supply. So integration can be considered under two basic categories, the natural system and the human system. Integration occurs both within and between these categories, taking into account variability in time and space.

Nowadays, the planning studies are also confronted with a growing complexity. The systems to be managed become larger and more complex due to the need to consider WRM on a more integrated scale. This requires management strategies and a systematic procedure for the analysis of the system and the evaluation of alternative courses of action. For example the water demand by the different users in the lower reach of the Yellow River is much higher than the supply during most of the years. Moreover the number of users or user groups also increased in the last years, which makes the situation even more complex.

The water resources system (WRS), which includes the natural resource system as well as the water use categories and the legal and institutional structure consists of three subsystems (Van Beek, 2000).

1. **The Natural Resources System** (NRS), being the system of rivers, lakes, groundwater aquifers including its functions for the ecosystem and the infrastructure required to use the water resources;
2. **The Socio-Economic System** (SES), the water using and water related human activities;
3. **The administrative and Institutional System** (AIS), the system of administration, legislation and regulation including the authorities responsible for the management of the WRS and the implementation of laws and regulations.

WRM can be seen as an activity to match the users of the WRS (the SES) with the natural resources system (the NRS). The interaction between use and availability of the resources is controlled by the administrative and institutional system (the AIS) through which this management is effectuated. These three ‘entities’ are depicted in Figure 8. The arrows in Figure 8 only represent the actions, not the information streams.

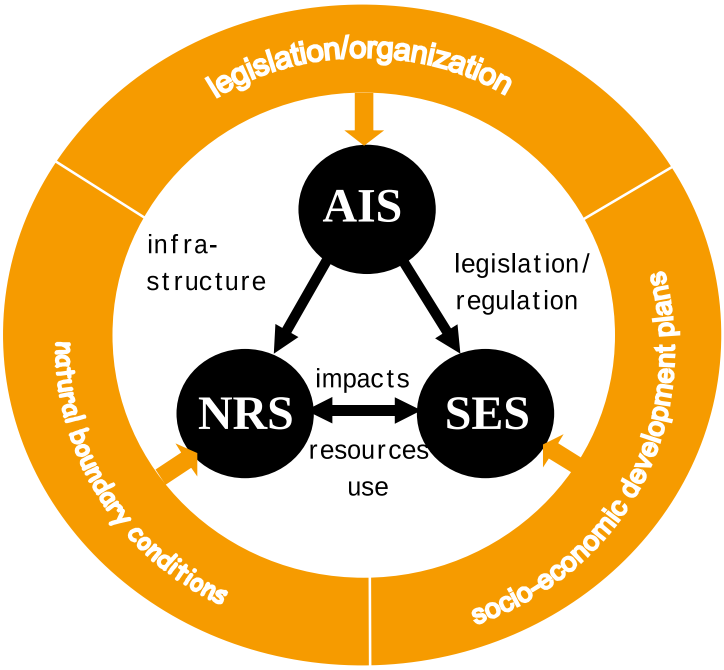


Figure 8: Context for water resources planning (Source: van Beek, 2000)

The AIS 'manages' the other two entities, using information about the present or expected future state of each system. The single arrows leading towards the two interacting systems depict the management actions of this system: by supply oriented measures for the NRS and demand-oriented measures for the SES. The interaction between the user system and the resources system is a physical one, depicted by the double arrow between the two systems. Resources provided by the NRS are used to support the SES and the SES (Van Beek, 2000).

Valuing the beneficial and the negative functions of the water resources systems is an essential part of the water resources planning. Comparing the value of one possible development path for the WRS with the value of another development path is a basic activity in water resources planning. If one wants to assess different development paths one should know which functions are at stake, how these functions will be affected by the different development paths, and which values can be assigned to these changes of functions. Identification of the relevant functions of the WRS is thus the starting point for the analysis. To do this, first the main system characteristics of the NRS, AIS and SES of the lower reach of the Yellow River have been described.

## 2.2 ANALYSIS OF THE NATURAL RESOURCES SYSTEM (NRS)

### 2.2.1 WATER RESOURCES IN THE YELLOW RIVER BASIN

Precipitation is the most important water resource in the basin. The annual precipitation is concentrated in the period July until October. The average annual runoff of the Yellow River is 58 billion $m^3$ (1987). About 10 to 20% of the runoff is discharged in the period March until June and 60% is discharged in the flood season from July until October. The inter annual runoff distribution is also not uniform. The ratio between the maximum- and the minimum value can be up to 3.4. Since 1919, a dry period that was longer than 5 years occurred twice. The annual average runoff during these dry periods was 39 billion $m^3$. The total amount of groundwater in the basin is 40 billion m³ (excluding the interior basin). The exploitable amount of groundwater is 12 billion m³ per year. The distribution of the groundwater is not uniform in the basin (Li, 2001).

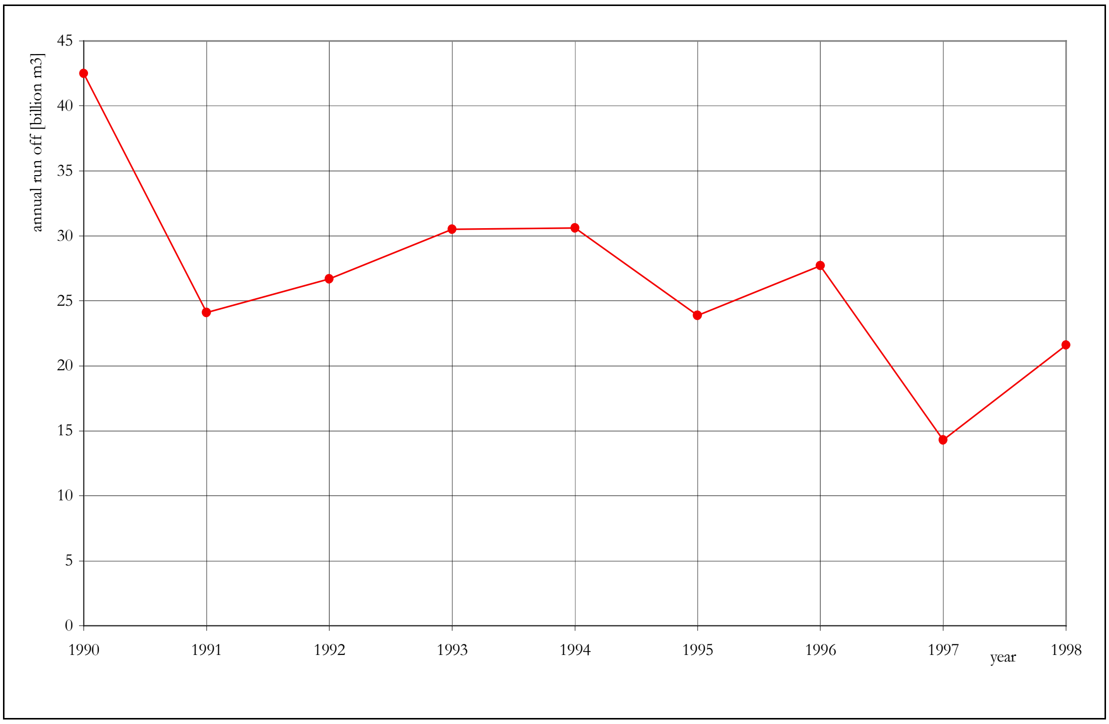


Figure 9: Annual run-off in the lower reach of the Yellow River

The average annual run-off in the lower reach of the Yellow River is 47 billion m³. The last decade the annual run-off is decreasing, see also Figure 9. The effect of the decreasing annual run-off is a decreasing sediment carrying capacity. The decreasing sediment carrying capacity results in more deposition and the build up of the bed level goes faster.

### 2.2.2 SEDIMENT IN THE YELLOW RIVER BASIN

The majority of the sediment sources in the basin are situated in the upper- and the middle reach. In the upper reach the average sediment concentration is only 6 kg/m³ and the average sediment transport is 142 million ton. In the middle reach the river flows through the Loess plateau. Due to the fine grain sizes and the restricted vegetation in the Loess plateau the soil erosion causes here a huge sediment load, especially during storms. During a storm the sediment concentration in the river can go up to more than 500 kg/m³ (Li, 2001).

One of the important characteristics of the Yellow River is that water and sediment originate in different regions. In the upper reach the annual sediment input is 9% whereas the annual run off is 54% of the annual input. In the middle reach the annual run off is 36% whereas the sediment input is 89%. From Xiaolangdi to the Bohai Sea, the lower reach, the surface area is limited and the annual run off depends mostly on the tributaries the Yilouhe and the Qinhe. The annual run off of the lower reach is 10% and the sediment input is 2% of the annual input. Due to severe soil loss in the middle reach on average 1.6 billion ton of sediment enters the river channel at Huayuankou annually, of which about 1.2 billion ton is carried out to the estuary region, leaving behind a substantial amount to contribute to the silting of the river channel(3). This results in high deposition in the riverbed of the lower reach. Due to this the riverbed fills up with on average 0.1 meter every year. Figure 10 shows the elevation of the riverbed between Xiaolangdi and the Bohai Sea in the period 1965-1997.

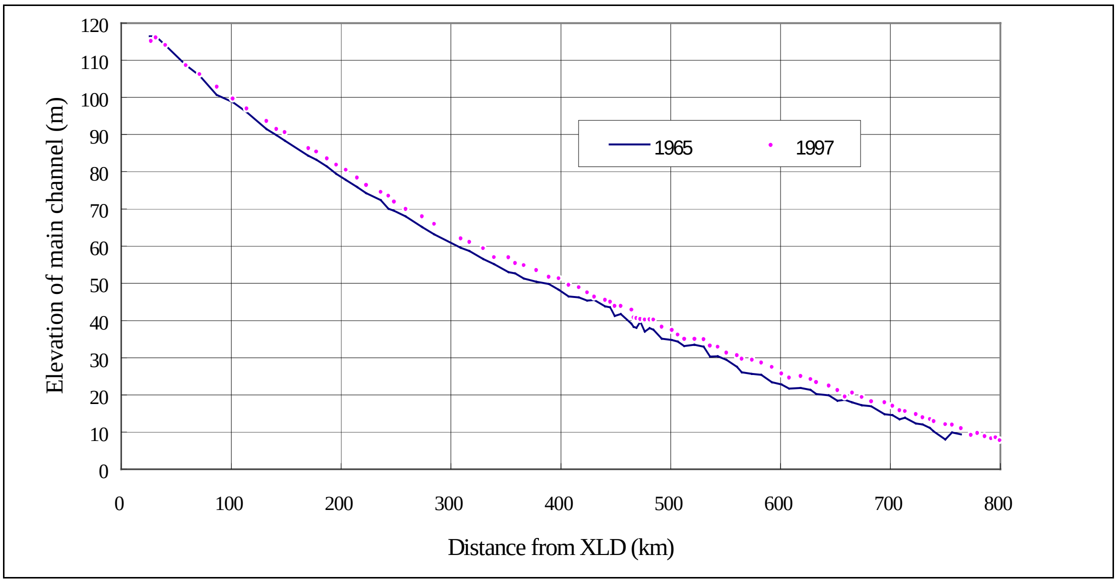


Figure 10: Longitudinal profile from Xiaolangdi (XLD= Xiaolangdi) (Source: LongYuqian et al, 2001)

In Figure 11 the Q/h relation for different years at Huayuankou is shown. This figure shows the impact of the decreasing flood conveyance due to the riverbed raising. Even for a normal peak flood of 5000 $m^3s^{-1}$ the water level raised about 2 meters in the period 1958-1996. It is expected that the process of bed level raising will continue in the near future. The reason for the peaks in the Q/h relation for 1982 and 1996 is unknown. A possible reason may be the bed level change at that stage or the breaching of unregistered dikes in the flood plain.

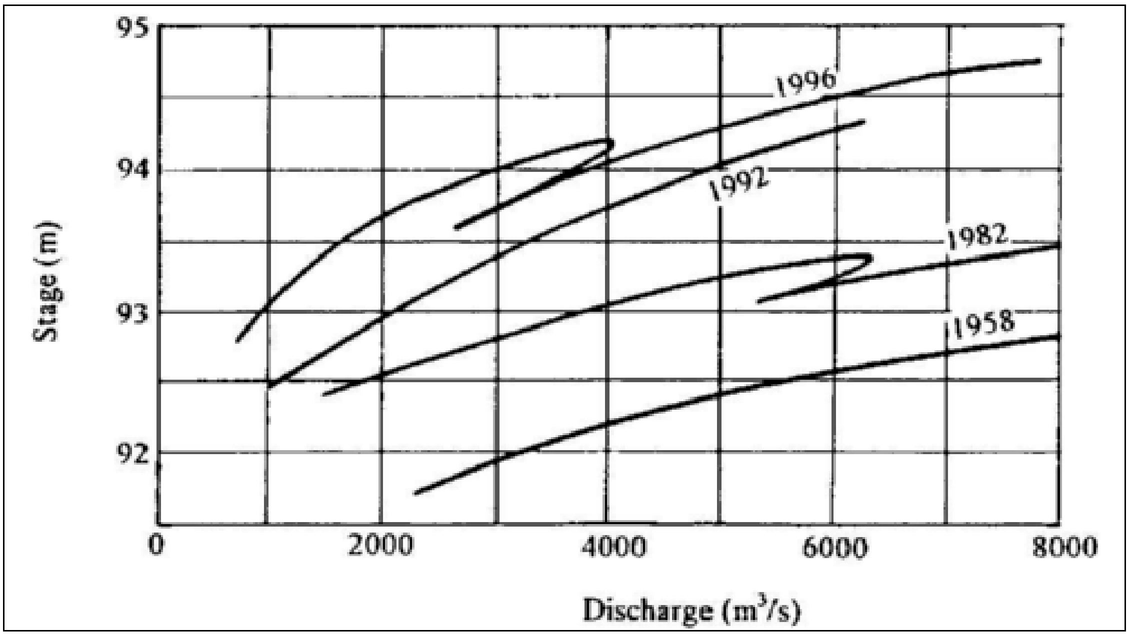


Figure 11: Water level-discharge relation for three floods (Source: Zhao-Yin Wang, 2001)

More in detail can be said that during the flood season (from July to October) deposition takes place between Xiaolangdi and Gaocun and erosion takes place downstream of Gaocun. Contrarily erosion takes place between Xiaolangdi and Gaocun and deposition downstream of Gaocun in the non-flood season (from November to June next year). But during the over bank flood period deposition takes place in the flood plains and erosion in the main channel. (Conversation with Zhang Yuanfeng, 2001).

According to the engineers of the YRCC the most important reason for the deposition in the LYR is the fact that most of the time the water/sediment ratio is not appropriate to carry the sediment to the Bohai Sea. This is also the main reason why the YRCC started to construct the Xiaolangdi dam. It gives an opportunity to influence the water/sediment ratio in order to reduce the deposition of sediment in the LYR. In a simple way the objective is to store the upstream water and only discharge from the reservoir with a water/sediment ratio that enables the water to carry the sediment to the Bohai Sea. The will be in full operation in 2003. In the first 8 years of the reservoir operation coarse sediment will be trapped and clear water will be released to the lower reach. About 0.3 billion ton of sediment in the lower Yellow River will be scoured by the released clear water and transported to the delta.

### 2.2.3 GEOGRAPHY OF THE YR LOWER REACH

The length of the river course of the lower reach is about 850 km and can be divided into three sections. The upper part from Xiaolangdi to Gaocun is about 310 km wandering stretch because of its unstable conditions (see section 2.2.4). The width of the main channel varies between 2000 and 5000 metres, see also Figure 12. Between Gaocun and Taochengpu the river is in a transition state; the length is about 155 km. Downstream of Taochengpu is a meandering stretch. Here the river length is about 385 km and the main channel width varies between 500 and 800 meters.

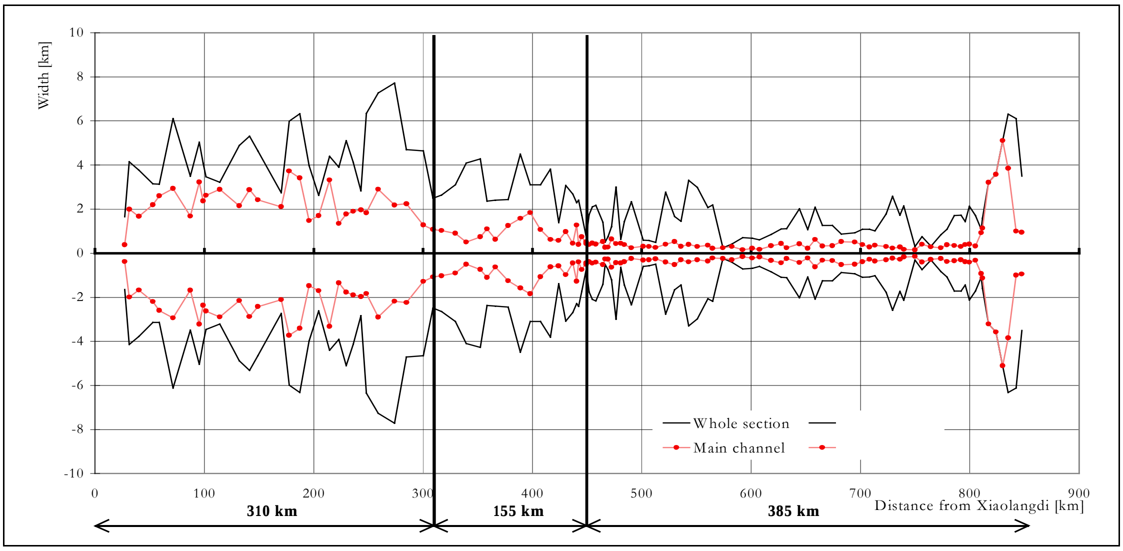


Figure 12: Variation of width in the lower reach (Source: LongYuqian et al, 2001)

### 2.2.4 MAIN CHANNEL AND FLOOD PLAINS

The main channel in the wide river course between Xiaolangdi and Gaocun is unstable. Because of the high gradient (about 0.02% upstream of Jiahetan, 0.01% downstream of Aishan) and the combination of low discharge and high sediment concentration, the main current of the river in its wide course segments varies frequently across the channel.

Consequently, the dike is often eroded and lashed by the main current. This was the major cause of dike-outbreak flooding in the history (Li Xiubin).

In general the flood plains in the lower reach can be divided in the low and the high flood plains. The low flood plains are the flood plains next to the main channel and the high flood plains are the flood plains between the low flood plains and the dikes, see also Figure 13. The flood plains are populated with a lot of people. In total 1.8 million people live on the flood plains in the lower reach. Except for the 1996 flood these high flood plains were not flooded in the last 100 years, not even during the flood in 1958 or 1982. Due to the rising bed level these flood plains were partly flooded in 1996.

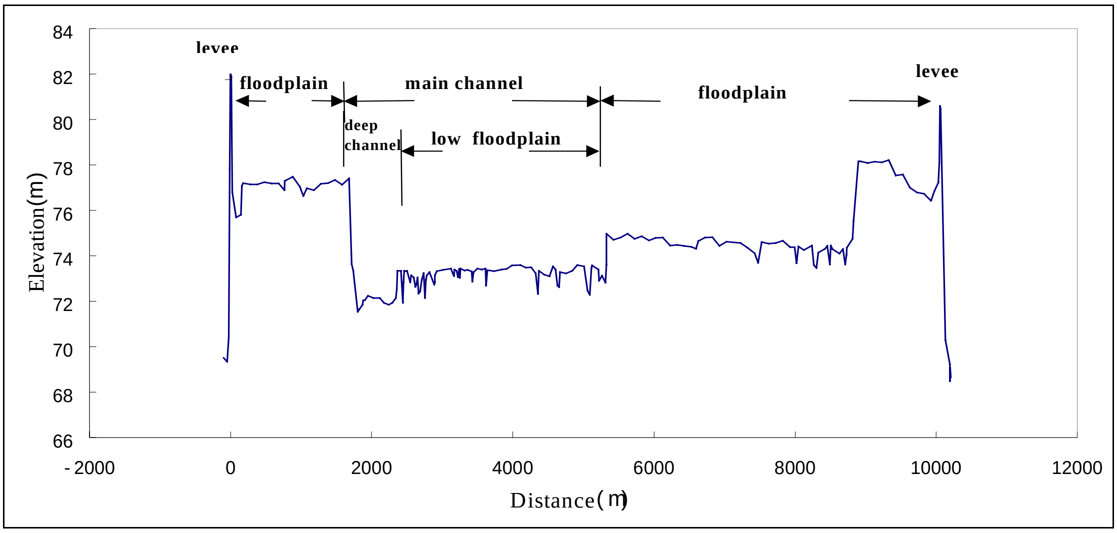


Figure 13: Cross-sectional definitions (Source: LongYuqian et al, 2001)

Most of the people living in the flood plain cultivate the land there. To protect their land and their crops against the water and the sediment of the river these people have built dikes in the flood plain, see also Figure 14. In this figure the cross-section is measured in May and October in the same year. Around position 3500 and 6500m on the x-scale dikes have been built. With the help of these dikes they tried to convey the flood within the main channel and therefore the flood was not able to use the part of the flood plain behind these dikes.

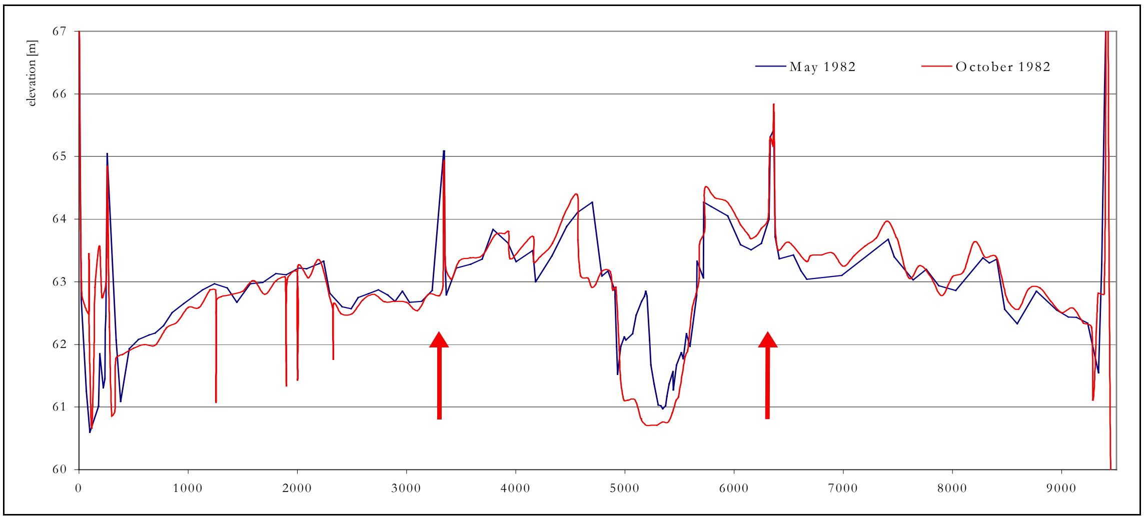


Figure 14: Cross-section in the lower reach in May and October 1982 (Source: YRCC)

In Figure 14 the main channel shift and the enormous erosion and deposition are well illustrated. During one summer (1982) the riverbed erosion was more than 3 meters at some places. On average the river erosion in the lower reach was 1-1.5 meters due to the flood in August 1982. Finally Figure 14 shows very clear the characteristics of the suspended river. The main channel is much higher than the flood plains and the flood plains are functioning like bathtubs. The elevation of the main channel is expected to increase faster due to the unregistered dikes in the flood plain.

### 2.2.5 DIKES IN THE YR LOWER REACH

Downstream of Huayuankou dikes along both banks confine the river, see also Figure 16. To control the ongoing riverbed elevation the dikes have been raised three times since 1949. Each time the crest was raised 1-2 meters. The total elevation due to the dike raising is 2-4 meters upstream of Jiahetan. Downstream of Jiahetan the total elevation is about 4-6 meters. The work was executed by renovating the old dikes, see also Figure 15.

Through strengthening and heightening the old embankments the elevation of the dikes was realised. The different colours represent the dike after each renovation. So the actual dikes are a combination of old embankments. Due to the construction on the original dikes there are a lot of hidden dangers and weaknesses in the dikes. There are many caved holes by animals like foxes.

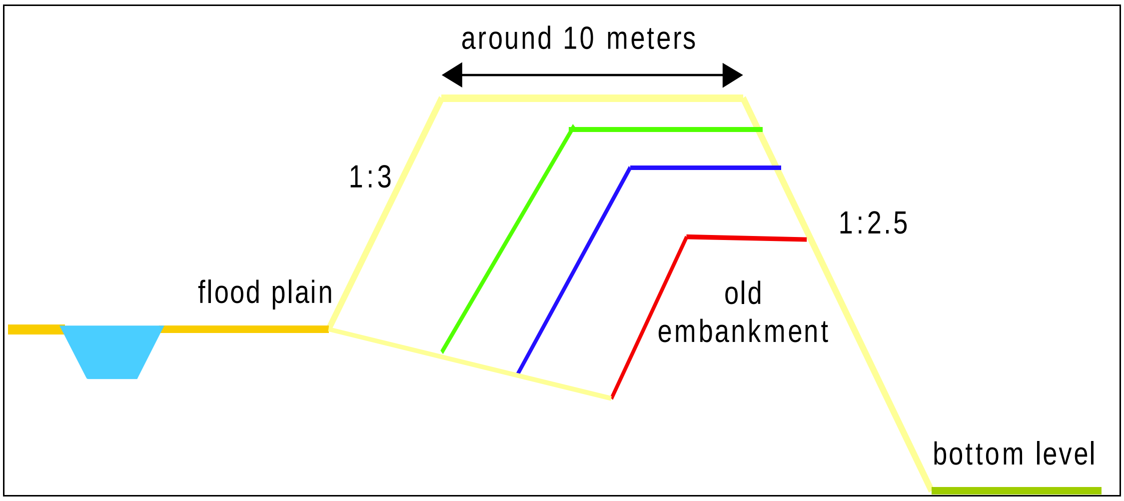


Figure 15: Average size of a dike in the lower reach

In general the height of the dikes is 10 meters. The design level, which is based on the design flood including a freeboard in accordance with Table 1, is not reached at all places. For 832 km the actual level is lower than the design level (Li Xiubin). There are many vulnerable spots in the 1300 km long dikes on the lower reach. The serious problems include loose dike bases, seepage, crevices and animal caves (Li Xiubin).

Table 1: Freeboard for the dikes in the lower reach (Source: YRCC)

| Section | Protection level above the design water level |
|---|---|
| Qinhe to Gaocun | 3.0 m |
| Gaocun to Aishan | 2.5 m |
| Aishan to Lijin | 2.1 m |

For 398 km the dike-sections are weak. In history most of the dike breaches did not occur because of overtopping of the water level but due to the scour of the toe of the dike. The toe eroded and finally the dike collapsed. Other reasons for dike breaches were scouring and overflowing due to insufficient height of the dikes.

### 2.2.6 RESERVOIRS IN THE YR LOWER REACH

The main reservoirs for the lower reach of the Yellow River are the Sanmenxia reservoir and the Xiaolangdi reservoir, see also Figure 16. Release from these two reservoirs and the confluence of the two downstream tributaries, Qinhe and Yilouhe; compose the inflow for the lower reach.

To protect the lower reach of the Yellow River against floods the Sanmenxia dam was constructed in the 1950's. This is a multi-purpose project located nearly 200 km upstream of Huayuankou. Due to enormous sediment deposition the reservoir lost its capacities and its operational policy became only flood detention. The outlet discharge capacity of the dam as originally designed was insufficient. After reconstruction of the outlets a new operational policy has been adopted for the Sanmenxia reservoir. In this policy relatively clear water is stored in the non-flood season from November until next June and during this period sediment is deposited. Water and sediment are discharged during the flood season including the deposits that were accumulated during the previous non-flood season (LongYuqian et al., 2001).

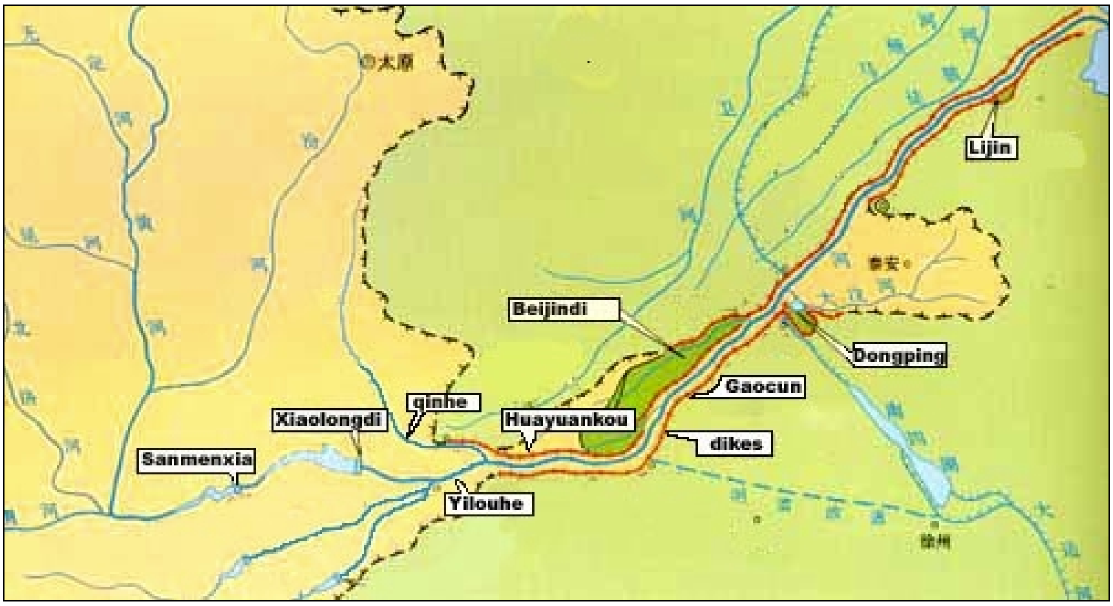


Figure 16: Tributaries, dikes, reservoirs and detention basins (Source: YRCC)

To further improve the safety for the people living in the lower reach and its flood prone areas the latest reservoir project is the Xiaolangdi multi-purpose project, located 130 km upstream of Huayuankou (Fischer et al, 1999). The most important objective of the dam, constructed by the YRCC, is to prevent dike breaches in the lower reach of the Yellow River or to control the downstream flood. After the construction of the reservoir the flood control will improve significantly. It is supposed to decelerate the build up of silt in the lower reach and thereby improve the safety for the 70 million people living downstream for at least 15 years. The combined flood regulation operation of Xiaolangdi reservoir with the Sanmenxia reservoir will lower the 1/1,000 flood peak to 22,500 $m^3s^{-1}$ at Huayuankou, and enable control without using the Beijindi detention basin**(4**). According to an engineer of the design institute of the YRCC there are also a few negative effects due to the implementation of the Xiaolangdi reservoir. There are still flood control problems in the lower reach, although many people may think that there are not flood control problems anymore. During a flood Xiaolangdi will still discharge between 8000 and 10000 $m^3s^{-1}$.

The operational scheme of the Xiaolangdi project is restricted in a number of ways:

- The discharge must be less than 800 $m^3s^{-1}$ or more than 2600 $m^3s^{-1}$ otherwise there will be sediment deposition in the Shandong province. Above 2600 $m^3s^{-1}$ the river can carry the coarse material to the sea. It is interesting to mention that Shandong province disagreed with the Xiaolangdi dam because they are afraid that it will give high deposition in the part of the Yellow River flowing through Shandong province.
- There must always be a minimum discharge of 400 $m^3s^{-1}$ in order to fulfil the demands of the drink water and irrigation water supply in the LYR area.
- The water level in the reservoir must be above 200m to discharge water. Below a water level of 200m it is impossible to discharge at least 2600 $m^3s^{-1}$ for a six days period. To discharge at least 2600 $m^3s^{-1}$ for a six days period 1 billion $m^3$ of water is required. This restriction can also prevent icing in the LYR. With a certain minimum flow the water will not freeze during the winter. The minimum water level in the reservoir must be 205m for hydropower. The maximum level during the flood period is 215m.

After about 15 years, around 2015, sediment will fill 66% of the reservoir and the storage capacity of water will decrease from 12 to 4 billion $m^3$. In between it is expected that the riverbed in the lower reach will not rise due to the storage of the sediment in the reservoir. Around 2015 new measures have to be brought up to keep the downstream flood control at least at the same standard.

### 2.2.7 TRIBUTARIES IN THE YR LOWER REACH

The main tributaries between Xiaolangdi and Huayuankou are the Qinhe and the Yilouhe, see also Figure 16. The other tributaries in the lower reach have a maximum discharge of 200-300 $m^3s^{-1}$ and do not significantly influence the peak discharge during a flood.

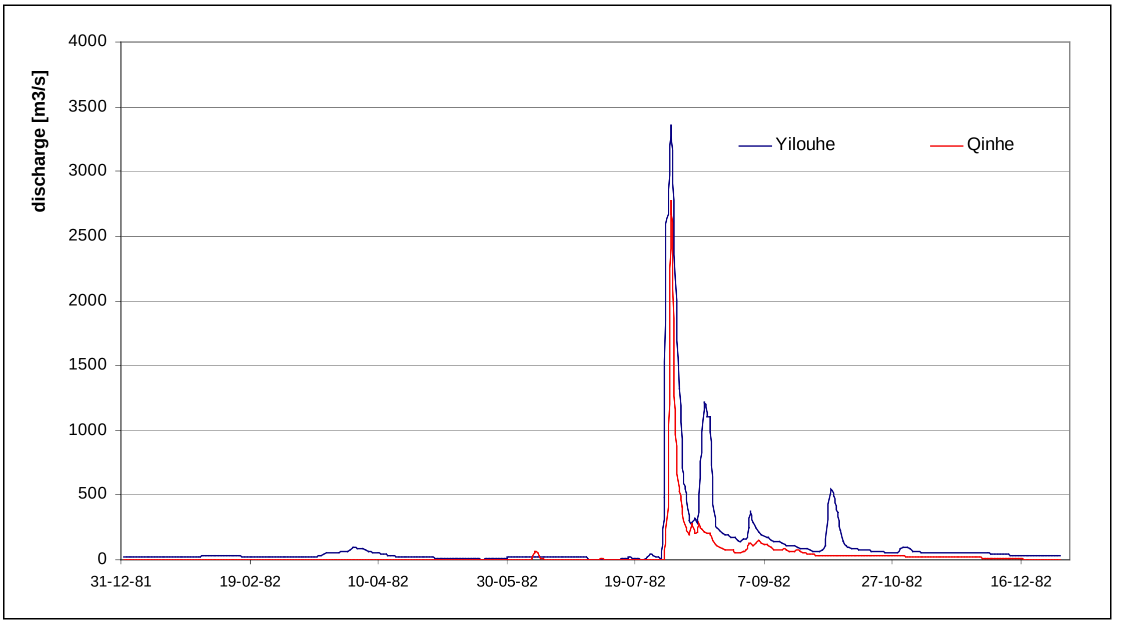


Figure 17: Discharge of the Yilouhe and the Qinhe in 1982 (Source: YRCC)

The discharge distribution of these tributaries during the year is very uneven, see also Figure 17. Most of the year the discharge is less than 200m$^3$s$^{-1}$. Only during July and August the discharge can increase up to 3500 m$^3$s$^{-1}$ and even higher. This is a normal pattern although only the year 1982 is shown in Figure 17. In terms of flood control the exact time of occurrence of the peak discharge in the tributaries is important for the total peak discharge in the lower reach. The design level of the Qinhe is 4000m$^3$s$^{-1}$ with a 1/20-year frequency. The design level for the Yilouhe is unknown but is expected to be at least the same as the design level of the Qinhe.

### 2.2.8 DETENTION AREAS IN THE YR LOWER REACH

There are five detention basins in the lower reach, see also Figure 16 or Figure 18. Nowadays totally 2.5 million people live in the detention basins. In Table 2 the total area and the storage area of each of the detention basins is described.

Table 2: Detention basins in the lower reach

| Name of basin | Area [km$^2$] | Storage [billion m$^3$] |
|---|---|---|
| Dagong | 2040 | 1.9 |
| Beijindi | 2316 | 2.0 |
| Dongping | 627 | 3.98 |
| Neizhan | 106 | 0.48 |
| Nanzhan | 123 | 0.33 |

According to the YRCC the two most important detention basins are Beijindi and Dongping Lake. Beijindi is situated in the study area and therefore only this detention area is described in this section. Inside the Beijindi detention area live 1.5 million people. The total detention area is 2316 km$^2$. In case a serious flood occurs more than 2 billion m$^3$ water can be stored in this area.


Figure 18: The five detention basins in the lower reach (Source: YRCC, 2001)

In total there are four inlet sluices. The inlet sluice situated at Qucun gate has a design discharge capacity of 10,000m$^3$s$^{-1}$. The current operation system is to withdraw water from the

Yellow River in case the discharge at Huayuankou is larger than 22,000 $m^3s^{-1}$. The water can be drained with the help of the Jindi river, which is flowing through the detention area. This river flows along the border of the detention area until the most downstream point and finally discharges in the Yellow River. Along the north side of the river the dike of the detention area is situated.

### 2.2.9 FLOOD PRONE AREAS IN THE YR LOWER REACH

Based on historical data the potential flood prone area in the lower reach is large. Upstream of Huayuankou the river flows through mountains and hills. Downstream of Huayuankou the area is flat. In case a dike breaches in the downstream area not only the Yellow River but also the Huaihe and the Haihe River basins are flooded. The total flood prone area downstream of Huayuankou is about 100.000 $km^2$, but these areas will not flood at the same time (also see Table 3).

Table 3: Potential flood prone areas including population (Source: YRCC)

| | Location of dike breach | Potential affected area [$km^2$] | Potential affected population ($10^6$) |
|---|---|---|---|
| North bank | Qinyukou-Yuanjang | 33000 | 16.4 |
| | Yuanyang-Taochengpu | 8000 | 2.5 |
| South bank | Zhengzhou-Lankao sanyizai | 21000-28000 | 23.4 |
| | Sanyizai-Dongping Hu | 13300 | 10 |

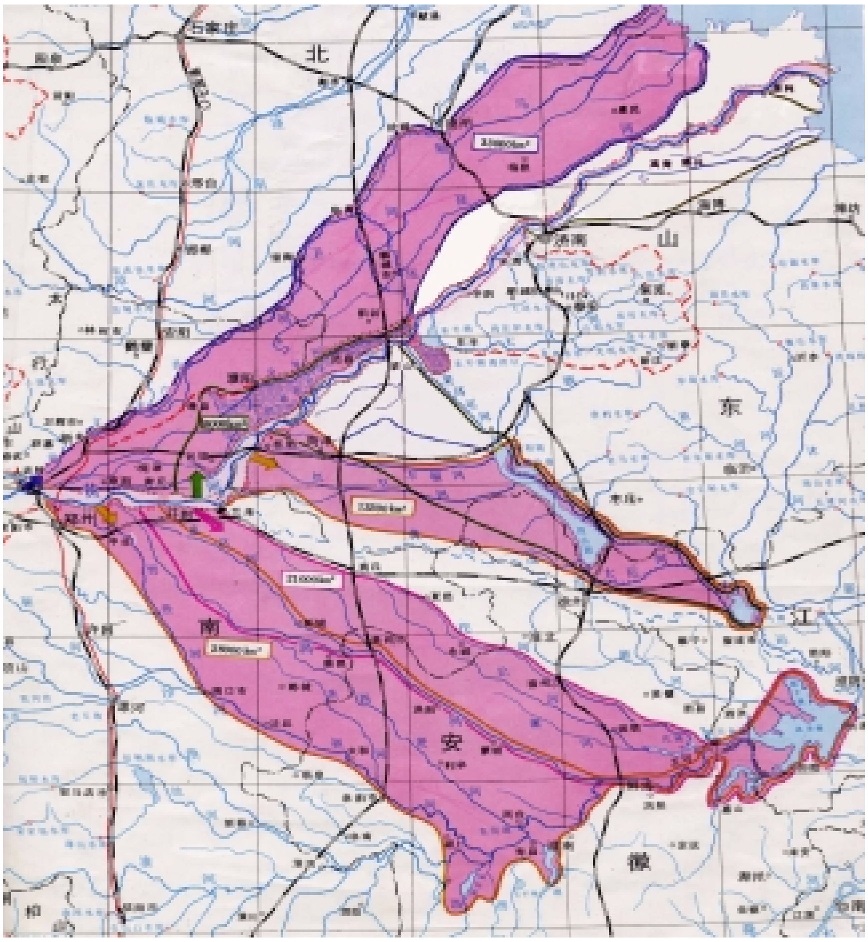

Figure 19: Flood prone areas between Huayuankou and Gaocun (Source YRCC)

In Table 3 the possible affected population is also mentioned. For example one dike breach on the north bank can threaten more than 16 million people. This is the same as the total population in the Netherlands. The potential damage to settlements and agricultural land in the event of embankment failure is high because the surrounding terrain is a flat plain (ADB, 2001). Therefore it is understandable that a dike breach can simply not be accepted anymore.

Figure 19 shows the geographical position and the extend of the flood prone areas. These areas are based on historical data. The largest flood prone areas, both at the north and the south bank, are positioned before the first detention basin. The second flood prone area on the north bank is the Beijindi detention area including an extra area that can also be used as a detention basin. Figure 19 also makes clear that the flood prone areas mainly exist due to the flood threat between Huayuankou and Jiahetan. Dike breaches in this section are responsible for 90% of the flood prone areas. This section is the most important section of the lower reach in terms of flood control. The section Huayuankou to Gaocun is even responsible for all the flood prone areas.

### 2.2.10 FLOODS IN THE YR LOWER REACH

There are two kinds of floods in the Yellow River: storm-caused floods that occur between July and October and ice jam floods, which normally occur in February (Li, 2001). The main floods of the Yellow River occur in July and August. The floods that occur in July and August are peak floods with a short duration that rise and fall quickly. Historical investigations show that the largest flood occurred in 1843, with a peak discharge of 36,000 $m^3s^{-1}$. The maximum flood measured occurred in 1958, with a peak discharge of 22,300 $m^3s^{-1}$ at Huayuankou (Li, 1999). This flood is used to determine the design level of the lower reach. The design level at Huayuankou hydrological station is 22,000 $m^3s^{-1}$ with a probability of once in 1250 years. The construction of the Xiaolangdi dam is not included in this design level. Table 4 shows the total flood frequency analysis for the lower reach of the Yellow River.

Table 4: Flood frequency analysis at Huayuankou (Source: Li, Rongchao, 2001)

| Item | Unit | Average | P=0.01% | P=0.1% | P=1.0% |
|---|---|---|---|---|---|
| Flood peak | $m^3s^{-1}$ | 9780 | 55000 | 42300 | 29200 |
| 5d flood discharge | b $m^3$ | 26.5 | 12.5 | 9.84 | 7.13 |
| 12d flood discharge | b $m^3$ | 53.5 | 20.1 | 16.4 | 12.5 |
| 45d flood discharge | b $m^3$ | 153 | 41.7 | 35.8 | 29.4 |

In spring often ice-jam floods occur between Huayuankou and the estuary. The riverbed slope is small in this part so the velocity of the water is low. The flow direction from west to east changes from low latitude to higher latitude at the Bohai Sea. This results in a higher temperature at Huayuankou than in the estuary. The average winter temperature near the estuary is 3.4 °C lower than at Huayuankou. For this reason in 80% of the years the river freezes-up and due to this in most of these years ice-jam floods happen. According to statistics, between 1950 and 1983 there were 29 years in which the river froze. In 1951 and 1955 serious ice floods occurred. The length of the frozen river was 550 km. and 623km. respectively. In history, the ice jam floods frequently broke dikes. According to rough statistics between 1883 and 1936, ice jam floods broke dikes in 21 years.

Table 5: Composition of the floods in Huayuankou (Source: Li, 2001)

| | | Huayuankou | | Sanmenxia | | |
|---|---|---|---|---|---|---|
| | Year | Discharge [$m^3s^{-1}$] | 12 d discharge [billion $m^3$] | Discharge [$m^3s^{-1}$] | Huayuankou [$m^3s^{-1}$] | 12 d discharge [billion $m^3$] |
| Upstream of Sanmenxia | 1843<br>1933 | 33000<br>20400 | 13.6<br>10.1 | 36000<br>22000 | 30800<br>18500 | 11.0<br>9.18 |
| Downstream of Sanmenxia | 1761<br>1958 | 32000<br>22300 | 12.0<br>8.9 | | 6000<br>6400 | 5.0<br>5.15 |
| Up- and down-stream Sanmenxia | 1957 | 13000 | 6.6 | | 5700 | 43.1 |

The extreme floods measured in Huayuankou are composed of different geographical sources and these foods also have different characteristics. A classification has been made for the different floods based on historical floods and for a few floods shown in Table 5. The classification is as follows:

1. The inflow upstream of the Sanmenxia reservoir and comparatively small inflow downstream of the Sanmenxia reservoir mainly compose the flood. This type of flood has a high flood peak, a large flood discharge, and a high sediment concentration.
2. The flood is mainly composed by the inflow downstream of the Sanmenxia reservoir. This type of flood has a rapid flood rise, a high flood peak, a low sediment concentration and a short forecast period.
3. The flood is composed half by the inflow upstream of the Sanmenxia reservoir and half by the inflow downstream of the Sanmenxia reservoir. This type of flood has a small flood peak, a long duration, and a low sediment concentration.

#### 2.2.11 WATER SHORTAGE IN THE YR LOWER REACH

Since 1990's the zero flow in the lower reach occurs more frequently than before. The times, duration and channel length increases gradually and the effect becomes more and more seriously. In 1997 the duration of zero flow in the lower reach of the Yellow River reached 226 days. In 1995 the length of the zero flow river reach was 683km, from estuary to Kaifeng. Due to the water shortage the sediment carrying capacity decreases and therefore the siltation in the lower reach is increasing. These droughts cause larger and larger losses of agriculture and industry and deterioration of the delta ecological environment as well. Obviously, the zero flow deteriorates the lower reach water quality and the ecological environment in the delta. The operational policy the Xiaolangdi reservoir enables to realise a continuous minimum flow in the lower reach of the Yellow River. The objective is to discharge 400 $m^3s^{-1}$ continuously in order to improve the water quality and to guarantee the drink water supply.

## 2.3 ANALYSIS OF THE SOCIO-ECONOMIC SYSTEM (SES)

### 2.3.1 SOCIAL ECONOMIC SITUATION IN THE YELLOW RIVER BASIN

The total population in the Yellow River basin is 98 million people (including the interior basin), which is 8.6% of the national population (1990). The total arable land area is 11.93 million hectare, which is 12.5% of the national arable land. The average population density is 123 people per $km^2$, which is a bit higher than the average national level. The population in the lower reach is 3% of the whole basin and the average population density is 624 people per $km^2$. The urbanisation rate is 23%. The GDP per head in the basin is 4533 RMB (Li, 2001).

### 2.3.2 POPULATION DISTRIBUTION IN THE YR LOWER REACH

Among all the provinces involved in the basin, the highest population is in Shanxi with a population of 25 million people. Whereas the lowest one is Sichuan, with only 70,000 (0.07% of the whole basin population).

Table 6: Population Survey in the lower reach of the YR (1999)

| Province | Basin area ($10^3$ km$^2$) | Population ($10^3$) | Population density (per km$^2$) |
|---|---|---|---|
| Shanxi | 96.5 | 18344 | 190 |
| Shaanxi | 133.1 | 24292 | 183 |
| Henan | 36.3 | 16232 | 447 |
| Shandong | 13.2 | 8397 | 636 |
| Total of the YRB | 794 | 97809 | 123 |

The population density in the provinces involved in the lower reach is uneven, see also Table 6. In this table only the population of the provinces involved in the lower reach is mentioned. The flood prone area in these provinces is larger and not taken into account in this table. Only the people living inside the basin are mentioned. Based on historical data 4 provinces in the lower reach can possibly be affected by floods. It concerns Henan, Shandong, Anhui and Jiangsu, in total 120,000km$^2$, where approximately 78 million people live.

### 2.3.3 INDUSTRY IN THE YELLOW RIVER BASIN

The industrial development is high in the basin. Hydropower resources are located in the upper reach, coal resources in the middle reach and petroleum and natural gas in the lower reach. That is why the basin is called “ the energy basin” in China.

There are 685 explored coalfields in the basin, which are mainly located in the middle reach. The total coal reserve is 449 billion ton (46.5% of the national coal reserve), and the predicted gross reserve is 1500 billion-ton. The explored petroleum and natural gas reserves, mainly located in the lower reach, are 4.1 billion ton and 67.2 billion m$^3$, 26.6% and 9% of the national gross reserves respectively. The iron reserve is 3.8 billion ton (until 1991), 7.7% of the national reserve. The total mine area is 11,000 km$^2$ and the gold production is the second highest in China.

### 2.3.4 AGRICULTURE AND FORESTRY IN THE YELLOW RIVER BASIN

The total land area of the basin is 79 million-hectare (including the interior basin). Only 17% is plain land and 75% consists of mountains and hills. The land use depends on landform, climate and soil characteristics and is variable. The cultivated area in the basin is 12 million hectare, which is on average 0.122 ha per capita, 1.5 times the national capita value. The forest area is 10 million-hectare and the grassland area is 28 million-hectare. Forest and grassland are mainly located in the upper- and middle reach.

In 1990 the agricultural production was 50 billion RMB, which is 6.5% of the national gross agricultural production. The crop production is 33 million ton, which is 8% of the national gross crop production. The cotton yield was 320,000 ton, which is 7.1% of the national cotton yield. Cereals, especially wheat, corn, grain and rice, are the main agriculture products in the basin. Based on the statistics of 1990, the cereal area is 80% of the total crop area in the basin, and the production is 90% of the total crop production. The Yellow River basin is one of the main wheat producing regions in China. The corn producing area is about 20% of the whole basin. Corn is planted in every province in the basin except in Qinghai.

In the basin forestry resources are comparatively scarce and uneven distributed. Until 1990 there was altogether 10 million-hectare of forest. The forest coverage rate is 10.8% (half of the national average value), and its capita forestland area is 626 $m^2$, 12.9% of the whole basin area.

### 2.3.5 HYDROPOWER RESOURCES IN THE YELLOW RIVER BASIN

In 1993 the hydropower-installed capacity was 45 million kW, which is 24.7% of the national installed capacity. The annual power production is 230 billion kWh, which is 27.5% of the national value. Its average annual electricity generation is 355 kWh. The tributaries of the Yellow River contribute about 26% of the hydraulic resources. In the basin there are altogether 100 hydropower stations whose exploitable installed capacity is higher than 10,000KW.

The latest project, the Xiaolangdi dam is partly financed by the World Bank. The estimated cost of the project totals 34.746 billion RMB including 25.519 billion RMB from the State and US$1.109 from the World Bank. The World Bank loan will be repaid with the money earned by providing electricity through hydropower. The installed capacity for Xiaolangdi is 1800 MW.

### 2.3.6 WATER ALLOCATION IN THE YELLOW RIVER BASIN

The total water supply does not meet the total demand. The difference between the demand and the supply is increasing in the recent years. This is one the main reasons why the YRCC decided to control the water allocation in order to obtain a more balanced distribution. The current water policy is first to meet the demand of the rural and urban residents and the industry. Second it is to ensure the water quantity for the lower reach sediment transport. Third it is the integration of the upstream-downstream water users relations, and the last focuses on reasonably exploitation and utilisation of groundwater.

### 2.3.7 WATER SHORTAGE IN THE YELLOW RIVER BASIN

Water shortage has become more and more serious in the last decades mainly due to the economic growth and the irrigation supplied agriculture. Currently, water has become a vital constraint for social and economic development in the water shortage regions of Northwest and North China including the Yellow River basin. The gap will be as high as 4 billion $m^3$ in 2010 and will reach 16 billion $m^3$ in 2050. Both quantity and quality water resources are the bottleneck of social and economic development in the lower reach, especially for agriculture, industry and the oilfields in the estuary region.

## 2.4 ANALYSIS OF THE ADMINISTRATIVE AND INSTITUTIONAL SYSTEM (AIS)

### 2.4.1 LEGISLATIVE AND EXECUTIVE STRUCTURE

The agencies involved in the WRM can be divided in legislative and executive organisations.
The legislative structure is organised, in descending order, as follows:

- state level: state congress
- provincial level: provincial congress
- city level: municipal congress
- county level: county congress

The executive structure is organised as follows:

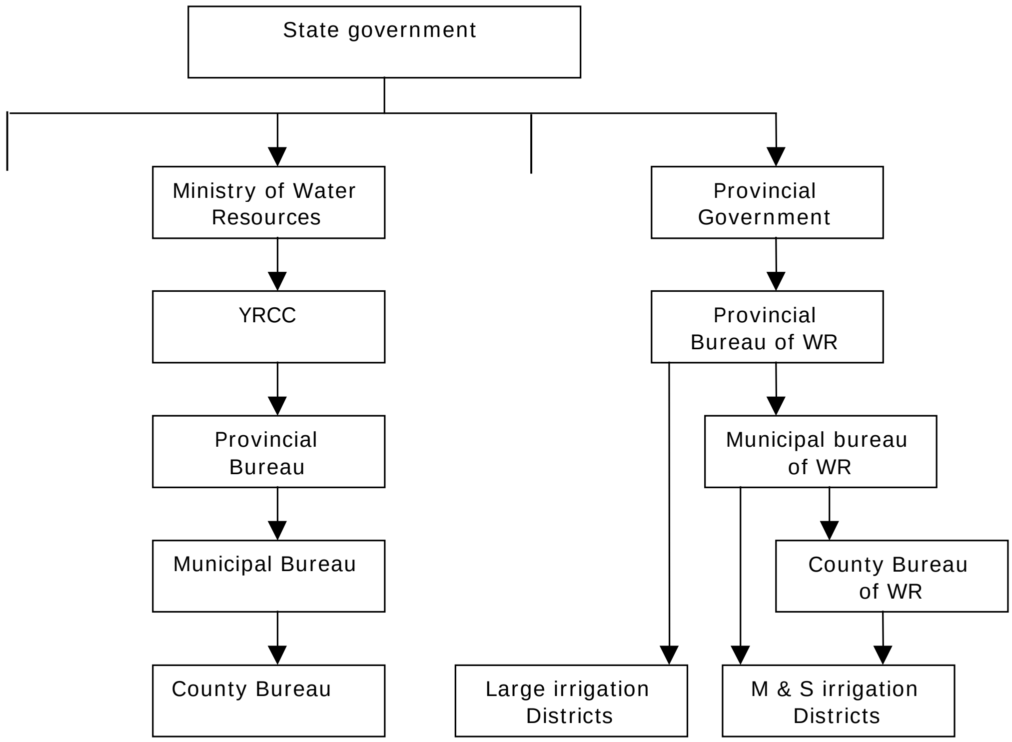


Figure 20: Executive structure of water management in China (Source: Li, 2001)

The YRCC (Yellow River Conservancy Commission) is the "executive body" of the MWR (Ministry of Water Resources) and responsible for the Yellow River affairs. The YRCC is a so-called subordination of the MWR.

Large-size water projects are managed by Basin Administrative Institutions that are subordinations of the MWR, such as the YRCC. Middle and small-size water projects are managed by Provincial, Municipal and County water administrative institutions respectively on the basis of ownership.

### 2.4.2 RESPONSIBILITIES OF THE YRCC

In general the responsibilities of the YRCC are:

- Organising and supervising implementation of relevant laws and regulations, notably the water law, and formulating basin-wide policies and regulations;
- Formulating a development strategy for the basin, and formulating comprehensive plans and technical plans in co-operation with other departments and provincial governments;
- Organising the monitoring, surveying & evaluation of water resources, formulating long-term water supply and distribution plans, and supervising their implementation; managing the water using license, and monitoring protection of water resources;
- Carrying out unified management of the rivers, lakes, etc., and managing part of the course of important rivers with the authorisation of the central government;
- Formulating a flood prevention plan for the basin, guiding provincial flood control plans and programs, co-ordinating daily work in flood prevention and drought resistance, and providing guidance to the safety and construction of the flood detention areas within the basin;
- Co-ordinating the solution of disputes on water among the provinces;

- Organising efforts of prevention, supervision and treatment in major areas of soil erosion within the basin, an guiding local efforts in water and soil conservation;
- Reviewing project proposals, feasibility studies and preliminary designs of projects under the central government, and those jointly funded with the local governments within the basin, and formulating the proposed plan on annual investment by the central government in the basin;
- Constructing and managing important water engineering projects of controlling nature or crossing more than one province, and responsible for the planning, surveying, designing, research and supervision of the important projects on the river and its major branches;
- Guiding work in rural and urban water structure management, hydro-power and rural electricity development; and

In the lower reach of the basin, the YRCC plays more an instrumental role in distribution decisions, whereas local water departments manage their own resources, the YRCC co-ordinates management and integrates the operation of the larger reservoirs. The Sanmenxia reservoir, for instance, is under the jurisdiction of the YRCC. The management of the Xiaolangdi reservoir, promises to be a controversial issue. If it is run under one set of operating priorities, it can drastically reduce the threat of flooding in the lower reach. On the other hand, a different set of priorities may enable Xiaolangdi to deliver much-needed hydropower to the energy deficient areas in the lower and middle reach of the basin. However, managing Xiaolangdi to achieve both ends simultaneously is impossible, and therein lies enormous potential for controversy. It is unknown whether a water or power agency will be chiefly responsible for Xiaolangdi, but this decision will have considerable impact on its efficient operation of the water system (Zusman, 1998).

YRCC has been particularly active in flood protection and in some cases it has developed and now manages multi-purpose water projects. Nevertheless a principle necessity is to enhance the institution capacity for integrating water management of the whole basin combined with provincial government and to reform the legislation for the multi-sectoral water management.

### 2.4.3 INSTITUTIONAL STRUCTURE OF WATER ALLOCATION

In 1999, in order to harmonise the opposing water-related interests and to avoid the zero flow (dry up) in the lower reach, the planning of the whole Yellow River water allocation is issued. The primary authority in the water allocation is the Central government, which delegates the responsibility to the YRCC. The YRCC has the authority to make the operational plan. The different stakeholders involved in the overall planning are summarised below.

1. National government:

The national government determines the general legislative and policy framework for water management. The national government issues rules to the quantitative management of surface water in the basin. This is important and even necessary whereas in general the allocation of water quantity for every province cannot meet its requirement. In the dry season the conflict among provinces is almost unsolvable.

Water resource management policies have traditionally been organised along narrow, sub-sectoral lines. Altogether there are 9 ministries involved in water management, see also Table 7. The current WRM framework in the Yellow River Basin makes the implementation of IWRM very difficult because different sectors rarely look at or have the interest in the impact of their actions on other aspects of the water resource management.

Table 7: Ministries and their relation with water management

| Ministry | Water subject |
|---|---|
| 1. Ministry of water resources | Surface water resource management |
| 2. Ministry of mining | Underground water management |
| 3. Ministry of construction | City water resources development, drinking water and sewage systems |
| 4. Ministry of agriculture | Agriculture water management |
| 5. Ministry of energy | Water and electronic construction |
| 6. Ministry of forestry | Protection of river basin forestry |
| 7. Ministry of transportation | Management of inland navigation |
| 8. Ministry of public health | Protection of drinking water |
| 9. Ministry of finance | Permission of flood control financing |

2. Yellow River Conservancy Commission

The main tasks of YRCC, in terms of water allocation, are as follows:

- To make the detailed rules of water allocation;
- To make the annually water allocation suggestion to the MWR;
- To make monthly and 10-days operational water allocation schemes;
- Supervising the scheme implementation of allocation plan in/by provinces and reservoirs.

Though the groundwater is exploited in the basin, the exploitation is free and is only restricted in cities by the municipal government. The exact quantity of the ground water, and its distribution in the basin, is not clear. Moreover it is still not mentioned in the Plan of Yellow River Water Allocation. At present, the allocation of the water resources just focuses on the surface water quantity in non-flood seasons in the basin.

3. Province

The province, in total nine for the Yellow River Basin, formulates the water policy for their own area according to the national legislative and policy framework. The province is also responsible for the operation of the surface water management. Provinces are involved in making the annual water allocation plan but their main task is to ensure the implementation of the plan. So each province has the responsibility to ensure the dredging of its boundary according to the water allocation scheme.

### 2.4.4 INSTITUTIONAL STRUCTURE OF RESERVOIR WATER ALLOCATION

There are 6 main reservoirs on the Yellow River that can be controlled by YRCC. The dominant reservoir on the upper reach is Liujiaxia; on the down reach it is Xiaolangdi. All of them are multi-purpose reservoirs. Due to the time and spatial concentrated distribution of the Yellow River runoff, reservoirs play an important role in water allocation and runoff regulation.

Hydropower groups have the authority to determine the power generation of each reservoir, and give the power generation scheme to them. Liujiaxia reservoir belongs to the Northwest power group. Xiaolangdi reservoir is belonging to the MWR. Because the storage of water and dredging of reservoirs tie up power generation, the power groups, especially the Northwest power group, are also involved in decision making and management with respect to the water allocation.

## 2.5 PROBLEM ANALYSIS

Looking at the WRS of the lower reach of the Yellow River as described in the last sections it can be concluded that fifty years have passed without any dike-outbreak flooding. One of the reasons is the dike elevation on the lower reach and the relatively low discharges. however it cannot be concluded that the danger of dike-outbreak flooding has been sufficiently prevented. In fact, the risk is still there and a number of reasons have even increased the risks. The reasons that the risk is still present include:

1. Low design flood discharge. The present design flood discharge of the Yellow River on its lower reach is 22,000 $m^3s^{-1}$ at Zhengzhou, which has a probability of 2.2%. This probability does not take the Xiaolangdi reservoir into account.
2. The construction of Xiaolangdi reservoir. If flood control and silt reduction will become the most important functions the Xiaolangdi project can improve the situation for about 15 years. Around 2015 new measures have to be brought up to keep the flood control in the lower reach at least at the same standard.
3. Poor quality of the flood control works. There are 832 km dike sections whose height is lower than the design water level because of the steady filling up of the riverbed. There are 340 km of weak dike sections.
4. Increasing danger of earthquakes. The lower reach of the Yellow River is located in a strong faulting area. It is predicted that in a large part of the area an earthquake of strength 7-8 on the Richter scale may occur within the future 50 years, and there is even a possibility of earthquakes of strength 9 in some areas (Li Xiubin).

The reasons for the fact that the risk has increased and is still increasing include:

5. Densely populated detention areas, of which the population is still growing. Beijindi detention area and Dongping Lake house millions of people and are therefore not suitable anymore to store water in case of a flood with a short forecast period (less than 24 hours).
6. Inside the flood-prone areas live approximately 78 million people. The industrial development is high in these areas and with that the economical importance of these areas is high. The potential flood damage has increased enormously in the recent years.
7. The increasing number of people living in the flood plain. The total number of people living outside the dikes in the lower reach is 1.8 million. Only for Henan province it is already 1.10 million. These people are very serious threatened by floods.
8. Decreasing flood conveyance capacity of the river channel. Owing to the construction of reservoirs on the upper reach and irrigation development in the whole basin, the discharge of in the main channel of the Yellow River has decreased and sedimentation on its lower reach has increased considerably in recent years. As a result, the water level with the same discharge is much higher than before.
9. The role of the YRCC in the distribution decisions for the reservoirs. The Sanmenxia reservoir is under the jurisdiction of the YRCC. The management of Xiaolangdi project is not yet known. If it is run under one set of operating priorities, it can improve the flood control in the lower reach. On the other hand, a different set of priorities may enable Xiaolangdi to deliver the economically interesting hydropower.

Overall, it can be said that due to the decreasing flood conveyance capacity and the low design flood discharge, the probability of a serious flood increases rapidly. In case a flood would occur the detention areas cannot be used anymore because of number of people living in these areas.

The increasing population and the economic development would cause much more economical damage in case of flooding than ten years ago. Moreover it can also be expected that the number of casualties will be much higher than ten years ago. The laws and the executive authorities are not able to control the number of people living outside the dikes and the related unspecified dike building inside the flood plain.

When looking at the measures taken in order to control the river in the last fifty years, the approach has focused on flood prevention by raising and strengthening the embankments and the construction of dams like Sanmenxia and more recently Xiaolangdi. However it seems that the traditional methods are not able to find sustainable solutions and to create a sustainable and safe WRS for the LYR and the flood-endangered areas around this part of the river. The danger of floods is still there and, for the reasons mentioned before, the danger is even increasing. Therefore it can be interesting to look at the river and its management from a different point of view in order to look for other measures and strategies to improve flood control. There are many ways to do this. The one that is chosen for this project is based on the Room for the River policy implemented on the Dutch river system because the Netherlands is facing the same kind of problems (although at a smaller scale) as the Yellow River.

The objective of this research is to find out the possibilities to adapt the Room for the River policy to the Yellow River and especially the lower reach. A 1D-model was set up to determine the effects of this policy and the measures put forward in the policy. The way of modelling and the data used to set op this model is described in the next chapter.

# 3 DATA COLLECTION AND MODELLING

This chapter describes the first part of the development phase. The development phase consists of the data collection and modelling and the preliminary analysis, see also Figure 21. The results of the data collection and the modelling activity are a 1D hydro-morphodynamic model, representing the characteristics of a part of the Yellow River. The required and collected data and the set up of the model are described in this chapter. The second half of the development phase, the preliminary analysis, is described in chapter 4.

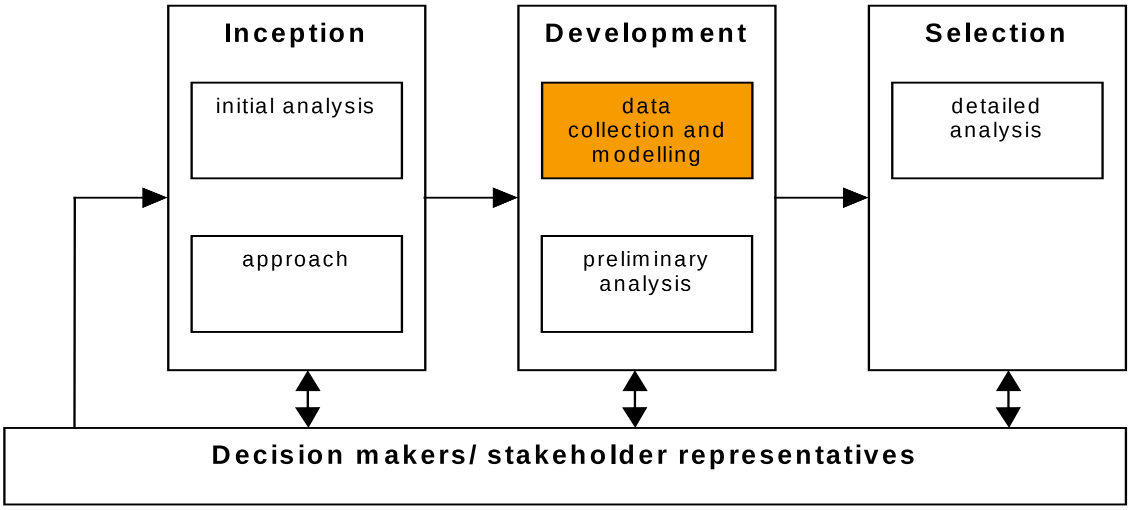


Figure 21: The first half of the development phase

## 3.1 PROBLEM IDENTIFICATION

Although there has not been a flood since the foundation of the PRC, a combination of facts has shown that the risk of floods is still there and due to a number of reasons the risk even increased in the last decades. In the previous chapter it was suggested to focus on a more integrated approach instead of only focussing on measures within the traditional engineering system in order to find ways to improve flood control. As part of the analysis it is useful to set up a model to determine the impact of the measures on the water level, discharge and bed level.

### 3.1.1 MORPHOLOGY

The Yellow River is the most heavy sediment laden river of the world. Therefore it is not surprising that the morphological processes play an important role in the water motion. To get an impression of the speed of the morphological changes due to interference in the river the morphological time scale can be used. The morphological time scale is a way to compare rivers with respect to the speed of degradation or aggradation. The morphological time scale $T_m$ is described in the following way;

$$T_m = \frac{L_m^2}{Y} \qquad [3.1]$$

where

$$Y = \frac{1}{3}\frac{b}{Bi}\int_{o}^{1year} S(t)dt$$

The average yearly sediment transport S in the Yellow River is 1.6 billion $m^3$. The storage width B of the river is around 5000m and the average slope i of the lower reach of the Yellow River is 1.5*$10^{-4}$. The variable b is the power of the sediment transport formulae, in this case 4.6. $L_m$ is considered as a standard length of 200 km. Thus the morphological time scale is approximately 10 years. The morphological time scale was analysed more in detail by Kriele and de Vries, 1998. They concluded it is indeed about 10 years. Table 8 shows the morphological time scale for different rivers around the world. The rivers show a considerable difference in the morphological time scales. The morphological time scale of the Yellow River is the smallest one, so the processes of degradation and aggradation go relatively fast. The most important reason is the high sediment transport in the Yellow River.

Table 8: Morphological time-scale for various rivers (Source: Jansen, 1979)

| River | Station (distance from sea) | D [mm] | i*$10^{-4}$ | $T_m$ [years] |
|---|---|---|---|---|
| Yellow River | Huayuankou (700 km) | 0.1 | 1.5 | 10 |
| Mekong River | Pa Mong | 0.32 | 1.1 | 130 |
| Waal River | Zaltbommel | 2 | 1.2 | 2000 |
| Magdalena River | Puerto Berrio (730 km) | 0.33 | 1.2 | 200 |

For most rivers it is allowed to model floods without taking the bed topography change into account because the bed level change is negligible on a short-term scale. In the Yellow River, the relation between the bed level and the water level is so direct that it is impossible to calibrate a model without including the bed topography change. That is why the water levels and discharges were calculated with a morphodynamic model. The advantage is that the model can also be used to determine the long-term river response.

### 3.1.2 SPATIAL- AND TIME SCALES

This project considers both short- and long-term problems. The time scale is short-term, a period of a few days, when it comes to the impact of measures on water level and discharge during a flood in the Yellow River. The long-term scale, often a period of decades, is the morphological river response. The long-term scale for the Yellow River is smaller, only a few years, because of the relatively small morphological time scale.

The most important spatial dimension is the one along the river. Almost the whole lower reach of the Yellow River, which is about 800 km, faces flood control problems. Interference in the river system can affect the whole river and not only the study area between Xiaolangdi and Gaocun. The area of interest in terms of flood control is the section between Huayuankou and Gaocun. There are two reasons why the section Xiaolangdi to Gaocun was modelled instead of the section Huayuankou to Gaocun. First of all to analyse the impact of the tributaries the Yilouhe and the Qinhe on the lower reach. Second to minimise the errors at Huayuankou.

## 3.2 DATA COLLECTION

The data collection was mainly executed in China during the summer of 2001. The available data and the required data did not always match. The obtained data was divided into three categories. Firstly the data to identify the functions of the Yellow River. Secondly the data to set up and calibrate the 1D-model and thirdly the data needed for determining the feasibility and screening the measures.

### Description of the WRS

The information required to describe the WRS was partly obtained during the literature study and partly based on the information provided by the YRCC. The information obtained from the YRCC was mainly gathered during the interviews and the discussions with the engineers of the YRCC.

### Set up of the hydro-morphodynamic model

To set up and calibrate the hydro-morphodynamic model the cross-sections, water levels, discharge, grain sizes and sediment concentration of the river were needed. The YRCC provided this information for the year 1982. During this year one of the highest flood peak occurred since the foundation of the PRC. The following measured data were provided by the YRCC:

- Discharge for each day at Xiaolangdi, Huayuankou, Jiahetan and Gaocun
- Discharge for each day in the Yilouhe and in the Qinhe
- Water levels for each day at Xiaolangdi, Huayuankou, Jiahetan and Gaocun
- Sediment concentration for each day at Xiaolangdi, Huayuankou, Jiahetan and Gaocun
- Sediment concentration for each day in the Yilouhe and in the Qinhe
- Bed load grain sizes at Huayuankou, Jiahetan and Gaocun
- Suspended load grain sizes at Huayuankou and Gaocun
- About 25 cross-sections between Tiexie and Gaocun in May and October 1982

Furthermore a suitable sediment transport formula was required to set up the morphological part of the model. The available formula and the way the most suitable formula was chosen is explained more in detail in section 3.3.4. To validate the model a flood peak during another year can be used. This data was not available, but even if it was available it may not be useful due to the fast morphological changes that influence the conveyance capacity and the water levels. To get an impression of the river response and the long-term effect of measures the following data was required:

- Average monthly discharge at Xiaolangdi for a ten year period
- Average monthly sediment concentration at Xiaolangdi for a ten year period
- Q/ h relation at Gaocun
- Average monthly discharge and sediment concentration of the Yilouhe
- Average monthly discharge and sediment concentration of the Qinhe
- The erosion and deposition between Xiaolangdi and Gaocun between 1982-1996

Most of above-mentioned data were not available or only available as design data. Consequently it was impossible to analyse the long-term effects of the proposed measures.

### Analysis of the flood management measures

To screen the promising measures, the following data were provided;

- The dike heights of the left- and the right bank in 2000 including the design safety levels and the actual safety levels
- The design level of the lower reach of the Yellow River
- The inlets, outlets, area and the height of the detention basins

**Interviews**

During the data collection period a number of people of the YRCC were interviewed. The interviews mainly focussed on creating a better insight into the main problems of the river and the mechanisms responsible for the flood control. There were a few interviews with engineers involved in the Xiaolangdi project, during a field trip to the dam. The information gathered during the interviews significantly contributed to the data collection.

# 3.3 MODEL SET UP

## 3.3.1 SCHEMATISATION

In the model only the section between Tiexie and Gaocun is schematised. The section Xiaolangdi to Tiexie, about 25 km, is not incorporated because of the steepness of the slope ($8*10^{-4}$) and the high Froude numbers (larger than one) in this section. In this section the river bottom is covered with stones and morphological changes do not take place. Between Tiexie and Huayuankou there are two tributaries, the Yilouhe and the Qinhe, see also section 2.2. Both tributaries are schematised as branches of the Yellow River. The confluence of the Yilouhe and the Yellow River is located 45 km downstream of Tiexie. The confluence of the Qinhe and the Yellow River is located 75 km downstream of Tiexie.

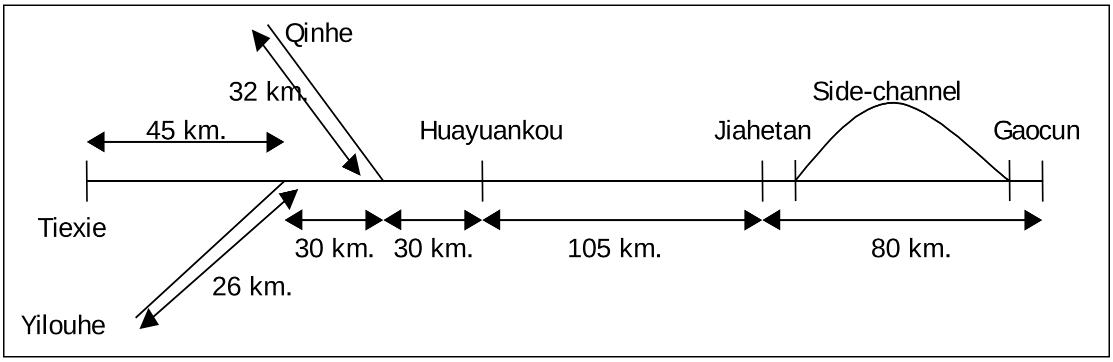


Figure 22: Schematisation of the project area

In the schematisation the length of the Yilouhe is 26 km and the length of the Qinhe is 32 km because the hydrological station of the Yilouhe is located 26 km upstream of the Yellow River, similar to the length of the branch. The hydrological station of the Qinhe is located 32 km upstream of the Yellow River. Downstream of Jiahetan a side-channel is schematised. This side-channel is schematised to incorporate the effects of the suspended river. The flood plains are schematised as a side-channel because there is no interaction between the flood plain and the main channel in this part of the Yellow River. The total schematisation is visualised in Figure 22.

## 3.3.2 BOUNDARY CONDITIONS

The discharge is used as the upstream boundary condition at Tiexie and the sediment load is used for the morphological boundary condition. The measured discharge was available at Xiaolangdi whereas Tiexie was schematised. Because of the shortness of this section and the high velocity of the water the measured discharge of the Xiaolangdi hydrological station is used as an upstream boundary condition at Tiexie. There is no matter of erosion or deposition in the section Xiaolangdi-Tiexie, like mentioned before, so the measured sediment load in Xiaolangdi hydrological station is used as upstream boundary condition at Tiexie.

The discharge and the sediment load are used as the upstream boundary condition of the two tributaries. At Gaocun the water level is used as the downstream boundary condition.

### 3.3.3 CROSS-SECTIONS

Between Tiexie and Gaocun 30 cross-sections have been measured. The average distance between the cross-sections is 10 km and the maximum 21 km. The cross-section schematisation was a complicated step of the model set-up. Due to the large number of unregistered dikes in the flood plain it is difficult to determine the actual storage area. Based on the measured cross-sections before and after the 1982 flood assumptions have been made about the actual storage area.

Another problem is the suspended part of the river, especially between Jiahetan and Gaocun. The flood plains are lower than the main channel and almost function like a bathtub. The problem is that Sobek River only accepts a cross-sectional area that increases with the flow stage. Separating the main channel and the flood plain in two independent channels solves this problem, see also Figure 22.

### 3.3.4 SEDIMENT TRANSPORT FORMULA

The commonly used sediment transport formulae, like the one of Engelund-Hansen and that of Meyer-Peter and Müller, cannot simply be adapted to the Yellow River. The high sediment concentration and the fine grains make it impossible to simply use one of the well-known sediment transport formula. The YRCC provided an article with a few well-known sediment transport formulae adapted to the lower reach of the Yellow River (Zhang Yuanfeng et al, 1999). One of them is the Engelund-Hansen formula and it seemed useful because it gives a fair prediction for fine sandy rivers with substantial suspended load. This formula was calibrated for a grain size greater than 0.025mm because the Engelund-Hansen formula calculates the total sediment transport, but does not include the wash load. The YRCC considers grain sizes smaller than 0.025mm as wash load. The calibrated Engelund-Hansen formula is defined as:

$$f'\phi_e = k\theta^m \qquad [3.2]$$

where

$$\phi_e = \frac{q_t}{\left(\gamma_s\sqrt{\frac{\gamma_s-\gamma}{\gamma}gD^3}\right)},\; f' = \frac{2g}{C^2},\; k = 0.015,\; m = 2.3$$

$q_t$ is the bed material discharge per unit width (kg/ms)

During the calculations it came out that this sediment transport formula was not suitable. The calculated sediment carrying capacity was too low. Adding a coefficient $\alpha$ to this formula solves this problem. The adapted formula is described as:

$$f'\phi_e = \alpha k\theta^m \qquad [3.3]$$

The exact value for α was difficult to find. By trial and error a reasonable sediment transport formula was found. The value used in this model is α=60. This means that the formula [3.2] is nowhere near applicable as an estimation of the transport rate.

### 3.3.5 GRAIN SIZES

The calculation of the morphology is related to the sediment transport formula and the sediment composition. The transported sediment contains two components, the bed material load and the suspended load. According to the mechanism of suspension the suspended sediment may belong to the bed material load and the wash load. The wash load is defined as the transport of material finer than the bed material. It has no relation to the transporting capacity of the stream (Jansen, 1979). The amount of wash load depends on the supply from the erosion in the catchment area upstream. In Figure 23 the classification to sediment transport is shown. The left side shows the classification to origin and the right side shows the classification like used in the sediment transport formulas. The bottleneck of the problem is the question which part of the suspended load is considered as wash load.

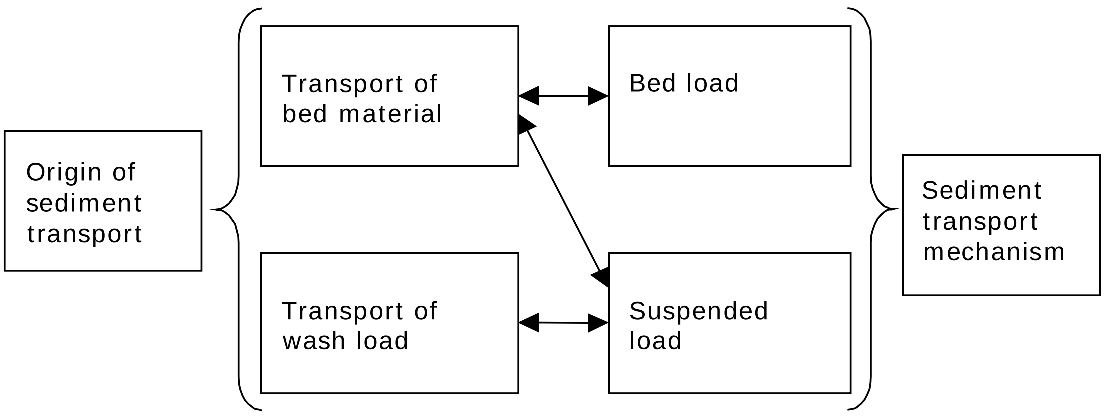


Figure 23: Classification to sediment transport

The measured data of the grain sizes of both the bed load and the suspended load are available. The suspended load was measured at Huayuankou and at Gaocun. The bed material was also measured at Jiahetan. The calibrated Engelund-Hansen formula only requires the D50 and the D90 of the bed material to calculate the sediment transport. For the model set up the D50 and the D90 at Huayuankou, Jiahetan and Gaocun were determined with the data of 15 measurements in 1982, see Table 9. For the section Tiexie-Huayuankou estimation was made based on the measured data of the other stations.

Table 9: Bed material grain sizes in July-August 1982

| Station | D50 [mm] | D90 [mm] |
|---|---|---|
| Huayuankou | 0.11 | 0.29 |
| Jiahetan | 0.08 | 0.22 |
| Gaocun | 0.09 | 0.21 |

The wash load component in the suspended load is determined with the help of the YRCC. According to an engineer of the YRCC the grain fraction that is smaller than 0.025mm can be seen as wash load. This is not totally correct because a few percent of the bed material in 1982 consist of the grain size smaller than 0.025 mm, see also Figure 24. Still it is gives a good indication and therefore it was used for the model.

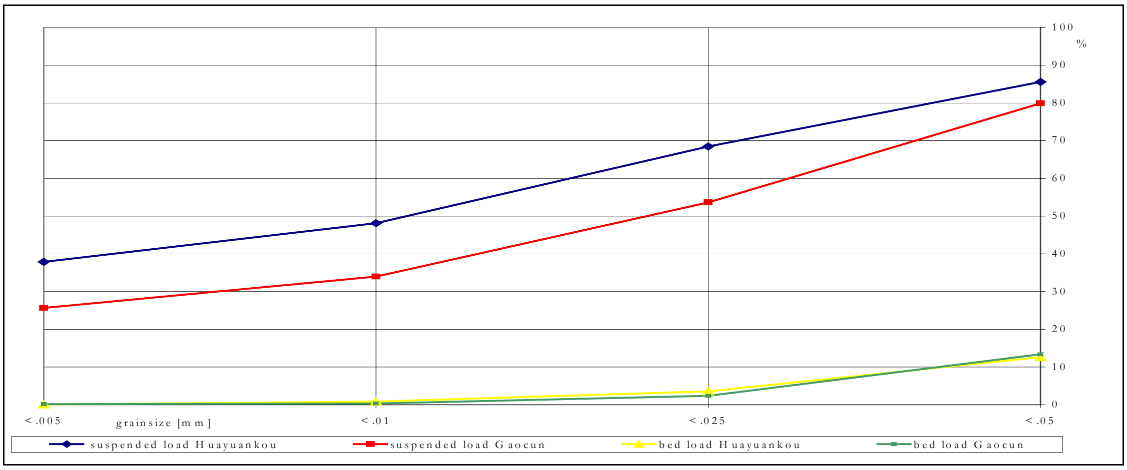


Figure 24: Grain sizes for both bed- and suspended load

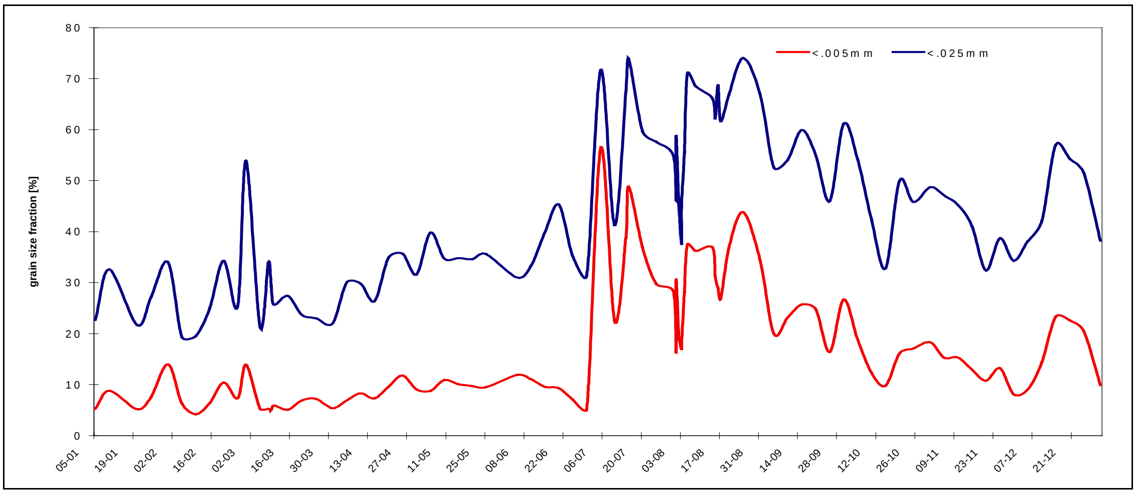


Figure 25: Grain size fraction of the suspended load at Gaocun

The sediment concentration used as upstream boundary condition was calculated by removing the fraction smaller than 0.025mm from the measured suspended load. Up to 75% of the suspended load consists of wash load, see also the graph in Figure 25. The remaining part is used as boundary condition. The suspended load composition is varying through the year, see Figure 25. The difference in wash load is almost 50% through the year and that is why it must be taken into account for a long-term calculation.

### 3.3.6 FRICTION

The cross-section is divided in a main channel and a flood plain. The same division was made for the bottom friction. The Manning coefficient was used to simulate the bottom friction. In the main channel the Manning coefficient was low and varying between 0.008 and 0.009 (This can be compared with a Chezy-coefficient of 120 to 150). On the flood plain the Manning coefficient was around 0.03. The low Manning coefficient in the main channel indicates hyper concentration with turbulence damping. As a consequence the application of the Engelund-Hansen is questionable. The results obtained with the adapted Engelund-Hansen are reasonable. However it is recommended to do further research on the sediment transport formulae.

### 3.3.7 TEMPORAL AND SPATIAL STEP SIZE

The time step in the model used for both the flow- and the morphological calculation is four minutes. The grid size is 1000 meters. The flow velocity varies between 1 and 3 $ms^{-1}$. The related Courant number is smaller than 0.75.

## 3.4 CALIBRATION OF THE MODEL

The calibration of the model is carried out in two steps. First the flow part is calibrated and then the morphological part. The calibration is carried out for a flood during the first ten days of August 1982. The peak discharge of this flood was the second highest one since the foundation of the PRC. Only the discharge of the 1958 flood was higher. The sediment concentration was relatively low during this flood but still more than 200 $kg/m^3$ at some locations.

There are four hydrological stations in between Xiaolangdi and Gaocun that monitor the discharge, water level and the sediment concentration. The first one is Xiaolangdi, the second Huayuankou, the third Jiahetan and the last one Gaocun (also see Figure 5). During the flood period, the discharge, water level and sediment concentration were measured a few times a day at the four stations. Furthermore there are two hydrological stations between Xiaolangdi and Huayuankou that only monitor the daily water level. The results of the calibration of both the water motion and the water level are presented in the following subsections.

### 3.4.1 FLOW MODULE

The calculated discharge at Huayuankou agrees to an acceptable degree with the measured discharge (also see Figure 26). Acceptable because this calibration point is the first calibration point in 130 km. The total calculated volume of water is smaller than measured, although a correction was made by adding a lateral discharge with a maximum discharge of 1000 $m^3s^{-1}$. The expected reason for the difference is the rainfall between Xiaolangdi and Huayuankou that is not sufficiently taken into account in the calculation.

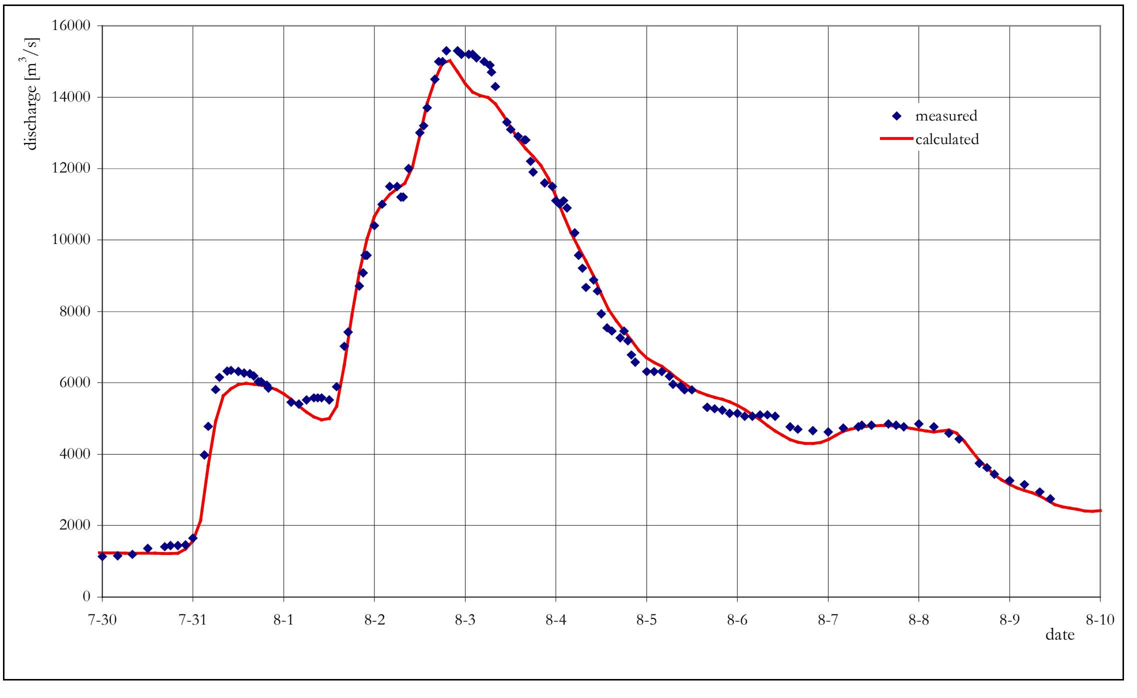


Figure 26: Measured and calculated discharge at Huayuankou

The difference between the calculated and the measured discharge at Jiahetan is acceptable (also see Figure 27). The peak discharge is the same, but it arrives later than in the measurements. Moreover, the measured discharge has two peaks, whereas the calculated discharge has only one peak. The reason for the two peaks in the measured data is because of the suspended river that originates between Huayuankou and Jiahetan. The water on the flood plains does not interact with the water in the main channel. The flow velocity on the flood plains, and hence the propagation speed of the flood wave, is different from that in the main channel. This creates two flood peaks.

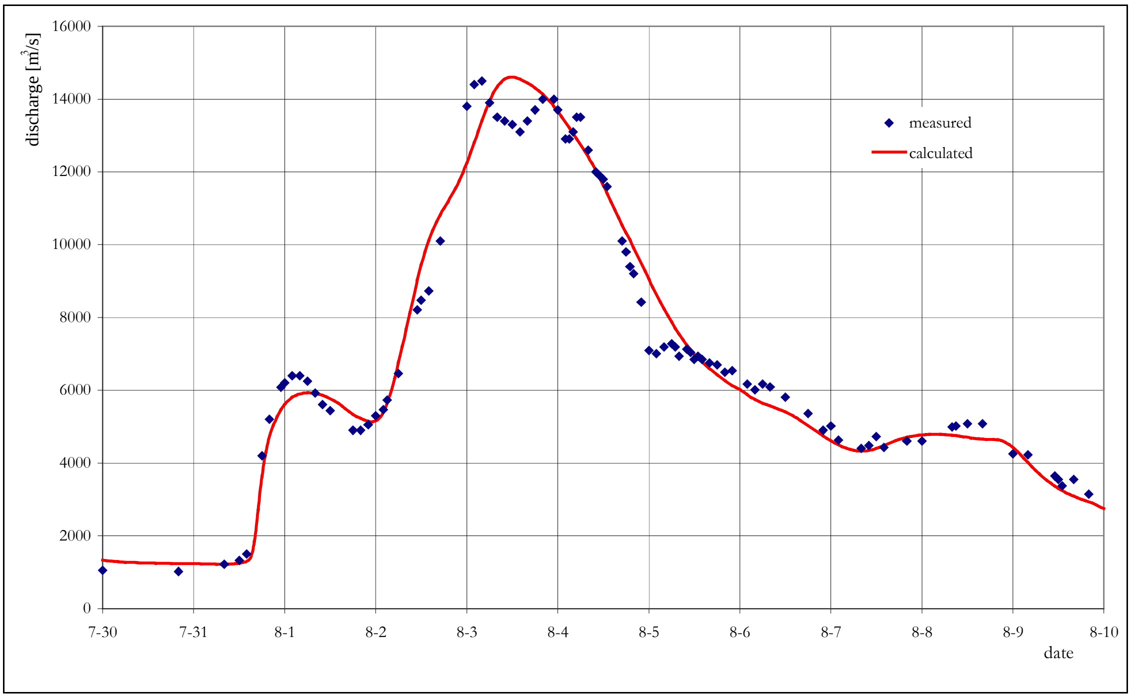


Figure 27: Measured and calculated discharge at Jiahetan

The difference between the measured and the calculated discharge at Gaocun is acceptable for a discharge less than 6000 $m^3s^{-1}$, above 6000 $m^3s^{-1}$ there is a significant difference (also see Figure 28). The shape of the measured flood peak at Gaocun differs from that at Huayuankou and Jiahetan. There are two reasons for this. Firstly the measured discharge has two flood peaks, like at Jiahetan. The reason is that the suspended river creates two channels, the main channel and the flood plain. The second reason is that the flood plains act more like a bathtub that starts filling up at a discharge of about 6000 $m^3s^{-1}$. This bathtub is schematised as a side channel in the model (also see section 3.3.1).

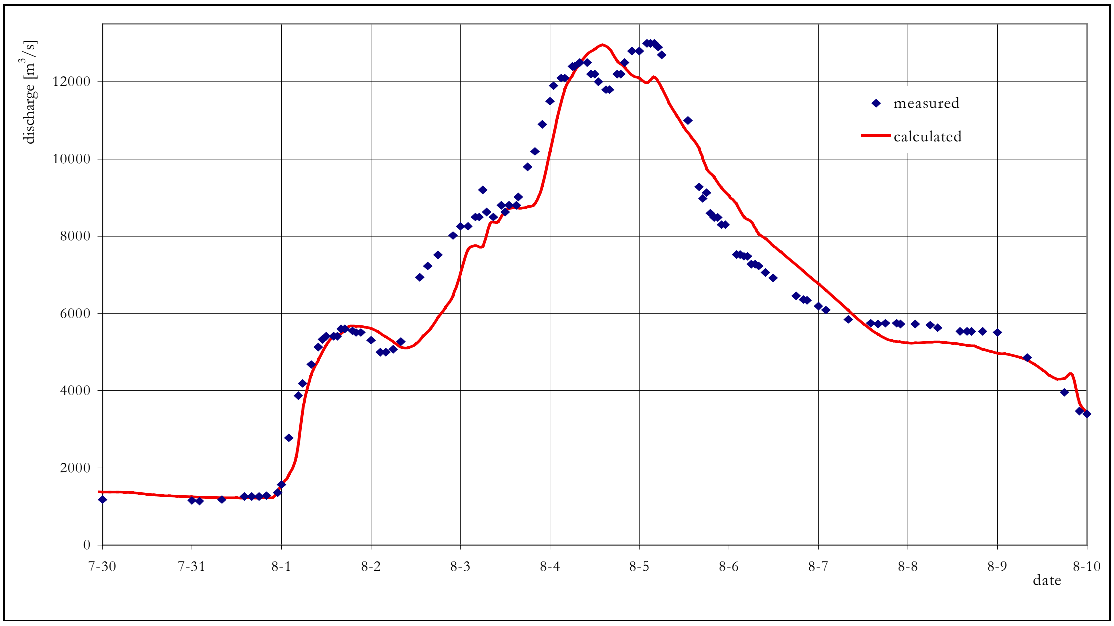


Figure 28: Measured and calculated discharge at Gaocun

The calculated water level at Huayuankou is acceptable for the first four days but after that the water level drops less than the measured water level (Figure 29). The maximum water level is the same as the measured one. The fact that the calculated water level drops less than the measured water level can have a number of reasons. One of them is the bed level variation during the flood peak. The average scour of the bed level during this flood was 1-1.5 meters. The scour at Huayuankou was 1-1.5 meters in the model, which is the same. But after 6 August there is a deposition of 0.5 m (also see Figure 37). In the next section it is shown that the bed level change has a significant influence on the water level, also on the time of occurrence of the change. This may explain that the water level drops less than expected. Another reason can be the cross-sectional area. This is also explained in detail in the next section. Although the water level is dependent on a number of factors, the calculated water level still gives a good indication of reality.

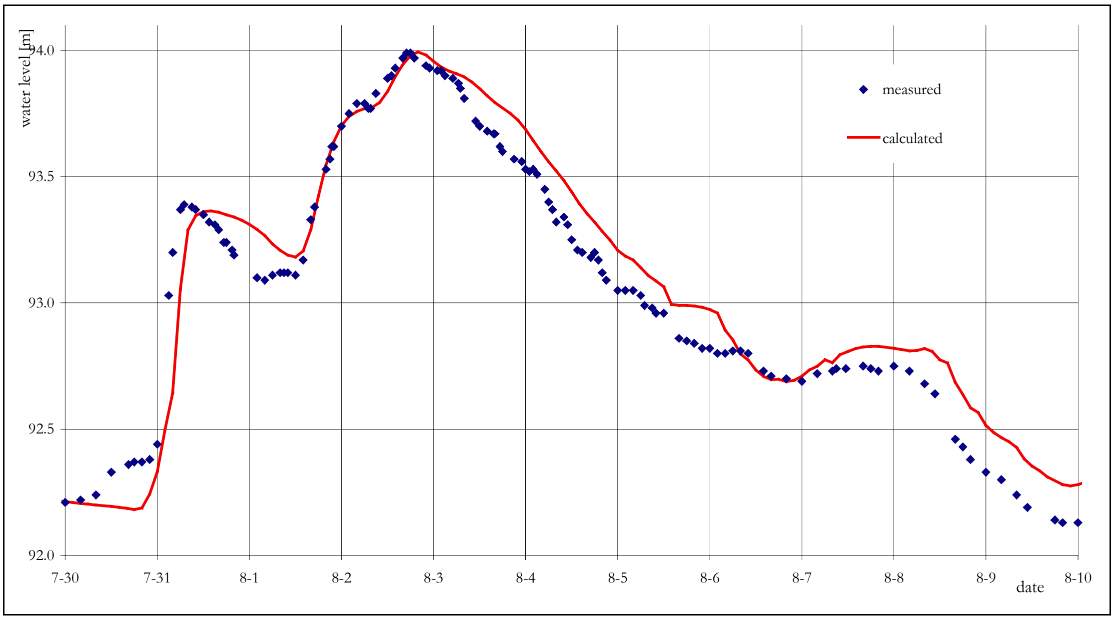


Figure 29: Measured and calculated water level at Huayuankou

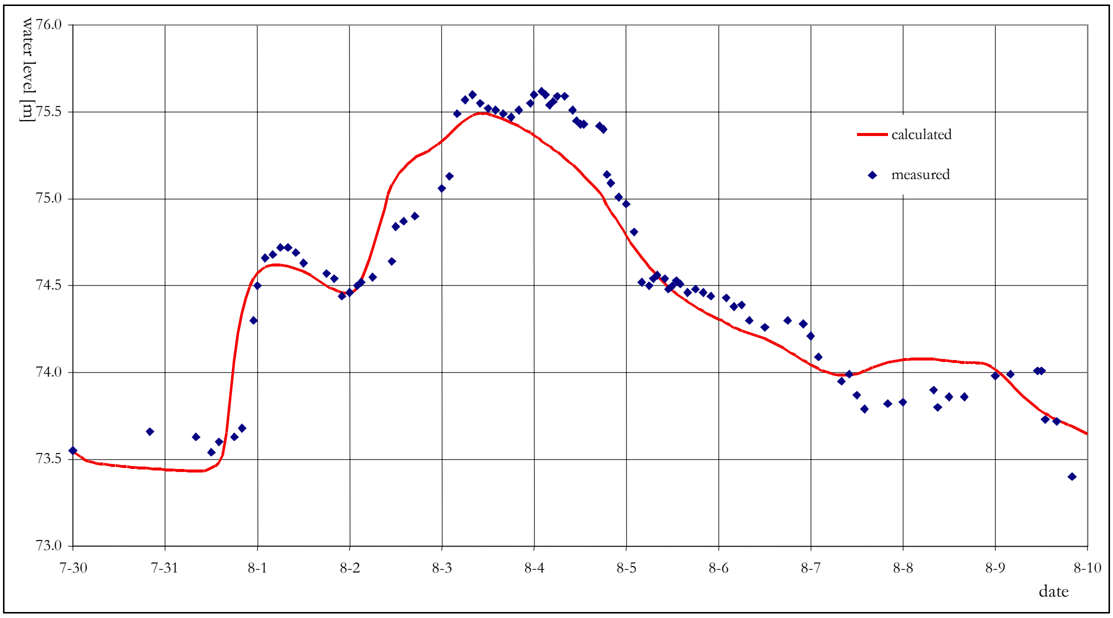


Figure 30: Measured and calculated water level at Jiahetan

The calculated water level at Jiahetan agrees less with the measured data than at Huayuankou (also see Figure 30). The difference between the measured and the calculated water level is about 10 cm. The calculated maximum water level is 10 cm below the measured value. The calculation of the water level at Jiahetan faces the same kind of problems as at Huayuankou. It is difficult to calculate the exact bed level change and, in addition, there is uncertainty about the cross-sectional area. Both factors influence the water level significantly.

In addition to the water levels of Jiahetan and Huayuankou the daily water level was measured for two stations in the section Tiexie and Huayuankou. The data of these stations only give an indication of the water level because there is variation within the day. The first one, station Peiyu, is situated 33 km downstream of Tiexie. The calculated water level in this station is plotted in Figure 31.

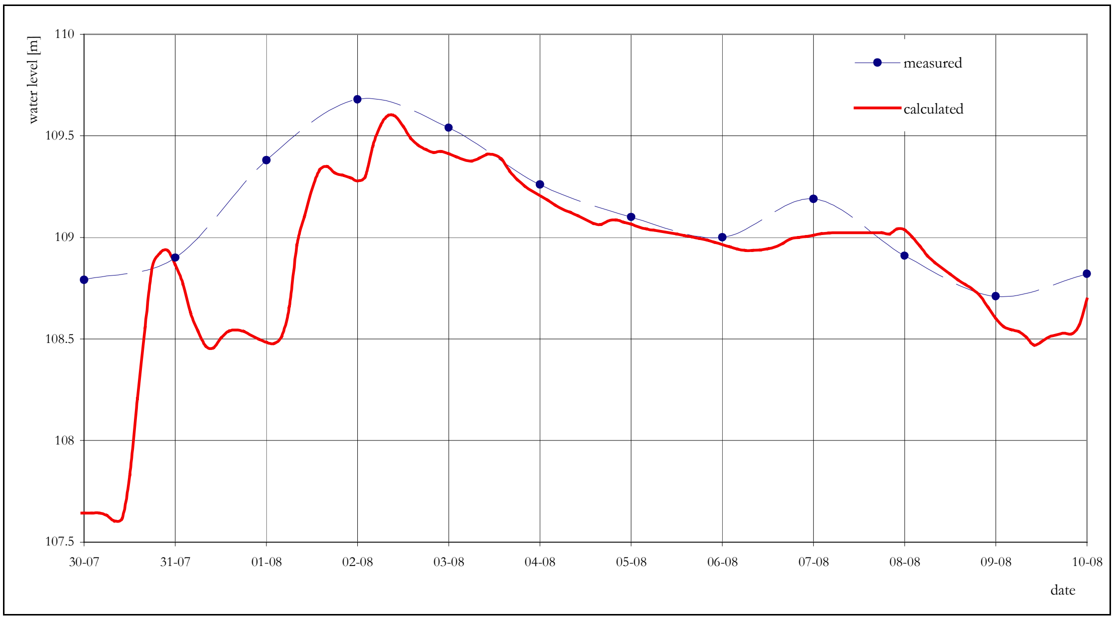


Figure 31: Measured and calculated water level at Peiyu

The other station, Guanzhangyu, is located 75 km downstream of Tiexie. The calculated water level in this station is plotted in Figure 32. For both stations the calculated water level is comparable with the measured water level, except for the first two days of August. The reason is unknown, but the measured water level at Huayuankou has the same pattern as the calculated water level at these two stations. The lack of data within these days may be one of the reasons.

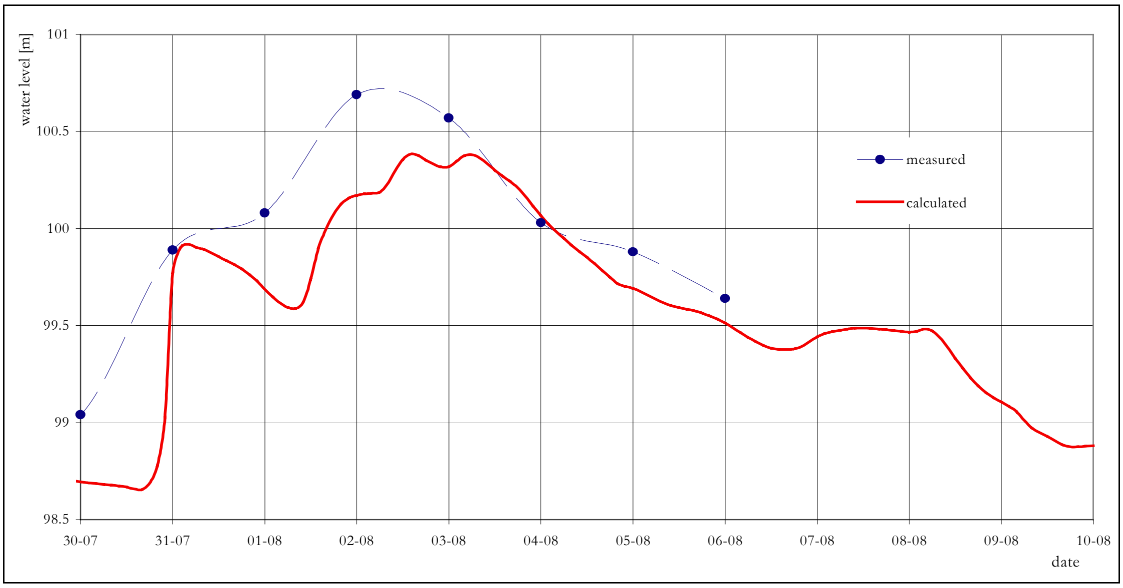


Figure 32: Measured and calculated water level at Guanzhangyu

### 3.4.2 MORPHOLOGICAL MODULE

The calibration of the morphology was carried out in two steps. First of all the model was calibrated with the sediment concentrations at the stations. Sediment concentrations are not often used for calibration but the concentration in the Yellow River is so high that at least it can give an indication. Second the morphology was calibrated with the erosion and deposition in the period May-October 1982. Also in this case exact numbers cannot be expected, but rather an indication in terms of erosion or deposition.

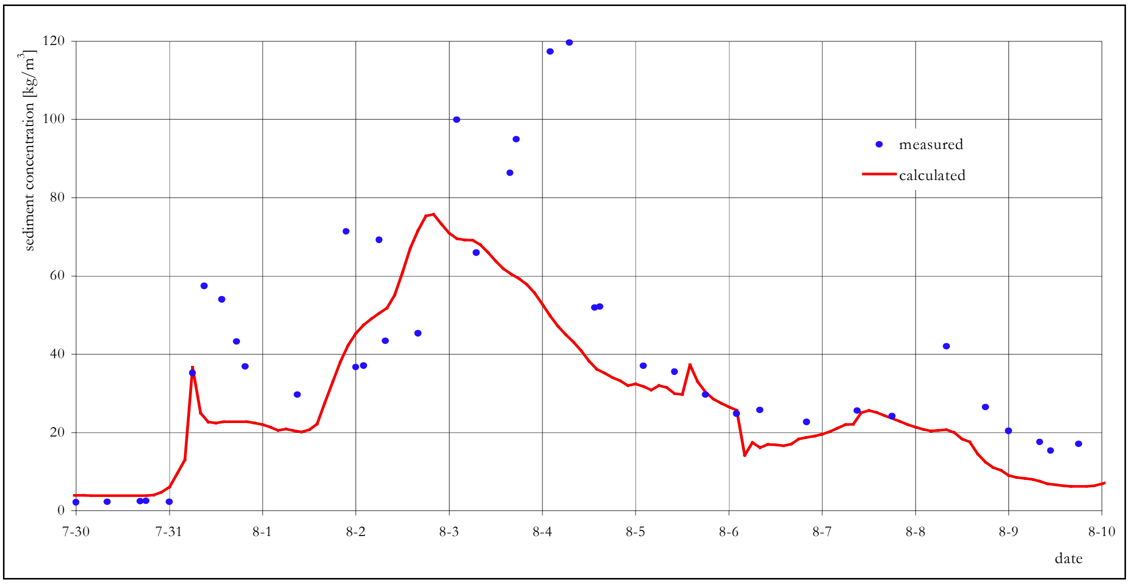


Figure 33: Measured and calculated sediment concentration at Huayuankou

The difference between the measured and calculated sediment concentrations at Huayuankou seems acceptable (also see Figure 33). The variation in concentration during the flood peak is followed by the calculated concentration. The most significant difference is the second sediment concentration peak around August 4, which is not followed by the calculated concentration.

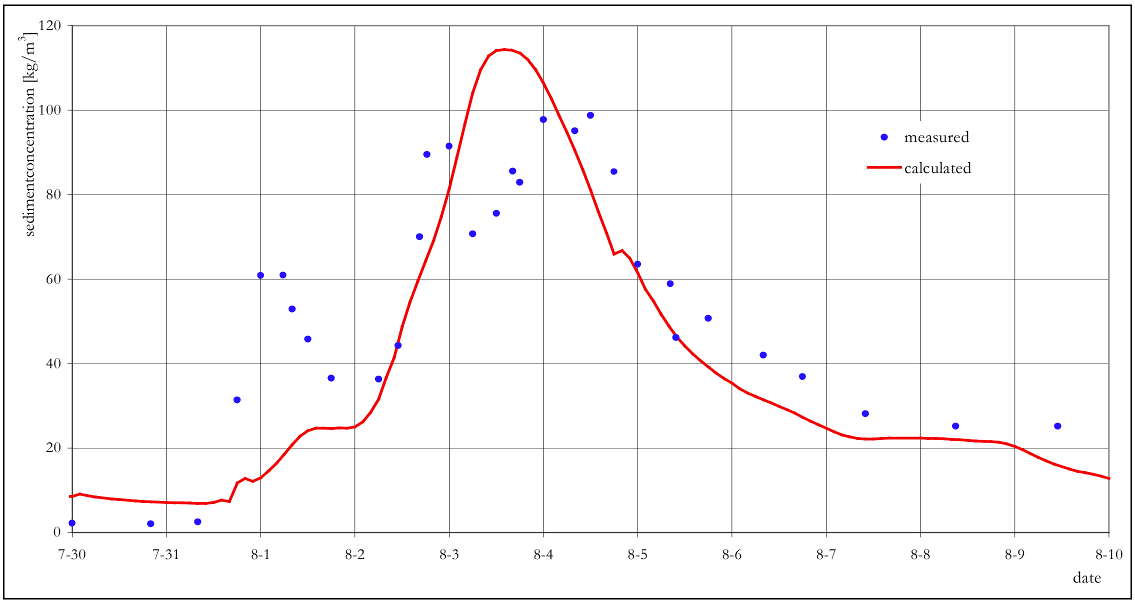


Figure 34: Measured and calculated sediment concentration at Jiahetan

The calculated sediment concentration at Jiahetan is acceptable compared with the measured sediment concentration (also see Figure 34). The maximum concentration is about the same. The most significant difference is the first concentration peak on August 1 that is not followed by the model.

The total increase in cross-sectional area is determined with the measured cross-sections of May and October 1982. The simulation with the model is also carried out for the period May-October 1982 with the daily discharge and sediment concentration data. The results of the measured data are compared with the calculated data, see Table 10.

Table 10: Measured and calculated increase in cross-sectional area

| Station | Distance from Xiaolangdi [m] | Model computation [m²] | Measured area [m²] |
|---|---|---|---|
| Peiyu | 59000 | + 75 | + 930 |
| Guanzhangyu | 101000 | - 240 | - 1100 |
| Huayuankou | 131000 | - 400 | - 161 |
| 230 | 148000 | + 400 | + 900 |
| 260 | 170000 | + 150 | + 35 |
| 270 | 187000 | + 600 | + 1580 |
| 280 | 204000 | - 400 | - 236 |
| Jiahetan | 236000 | + 850 | + 1076 |

The model computations for the cross-sectional change are comparable for most the stations between Huayuankou to Jiahetan, see Table 10. The calculated data fit less for the branch Xiaolangdi to Huayuankou. One of the reasons may be the estimated grain size for the section

Xiaolangdi to Huayuankou whereas the grain size on the section Huayuankou to Jiahetan is known. Another reason may be the confluence of one of the tributaries with the Yellow River at Guanzhangyu station.

## 3.5 BED-WATER LEVEL RELATION

In section 3.1 it was concluded that it is necessary to use a hydro-morphodynamic model to calculate the water motion, instead of using only a hydrodynamic model. The most important reasons are the high sediment concentration and the rapid bed level change during a flood. The influence of the bed level on the water level is computed with the model for the period May-October 1982. The correlation between the bed level and the water level is shown for the peak flood in August in Figure 35 through Figure 38. Each of the figures represents one of the hydrological stations. The difference between the red and the green line indicates the difference in water level with and without taking the morphodynamic changes into account. For each of the four figures the water level calculated with the hydro-morphodynamic model fits better to the measured data than the one calculated with the hydrodynamic model. This seems unexpected for the stations Peiyu and Guanzhangyu because the calculated increase of the cross-sectional area does not fit the measured data (Table 10). But the difference in water level with or without morphology computation is only compared for the first ten days of August whereas the increase in cross sectional area given in Table 10 refers to the period May until November.

The bed level evolution is also shown in each figure. When comparing with the water level, it is clear that there is a correlation between the two. In Figure 37, for instance the water level starts to change at the same point as the bed level decrease. The results fit the expectations, because in all four cases the agreement between compared and measured water levels becomes much better when the hydro-morphodynamic model is used.

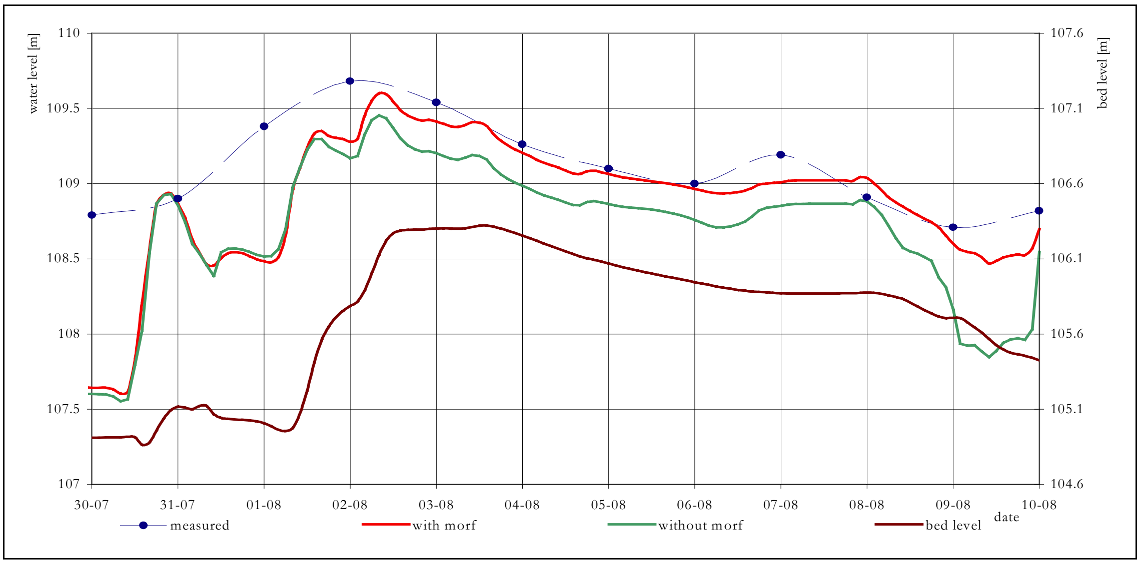


Figure 35: Influence morphology at Peiyu

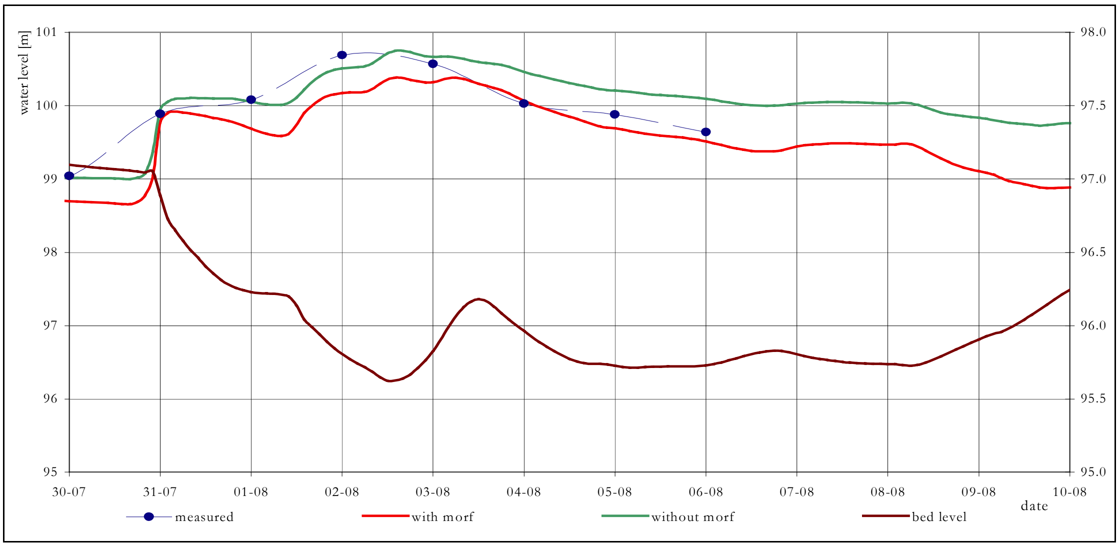


Figure 36: Influence morphology at Guanzhangyu

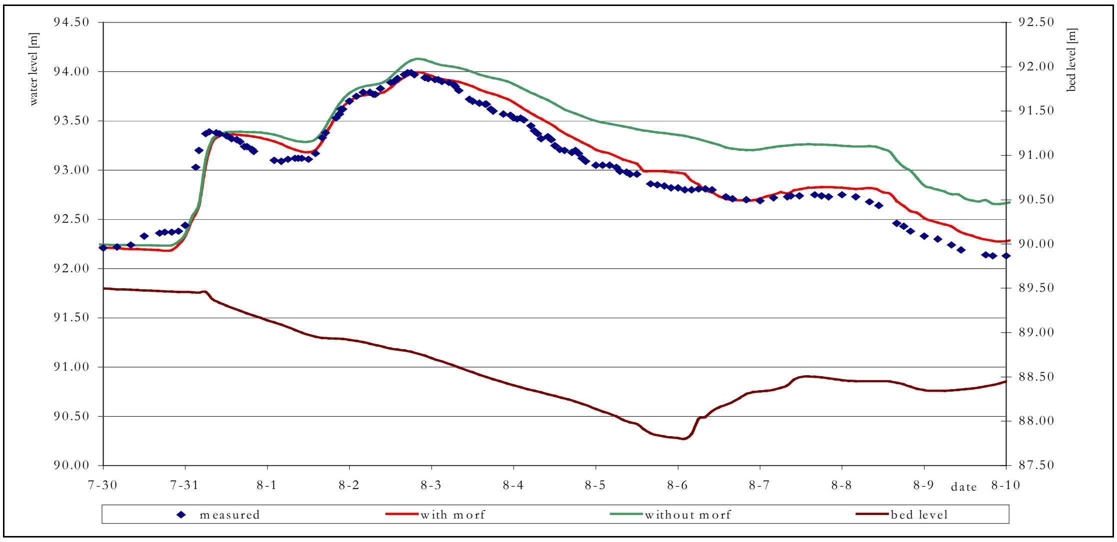


Figure 37: Influence morphology at Huayuankou

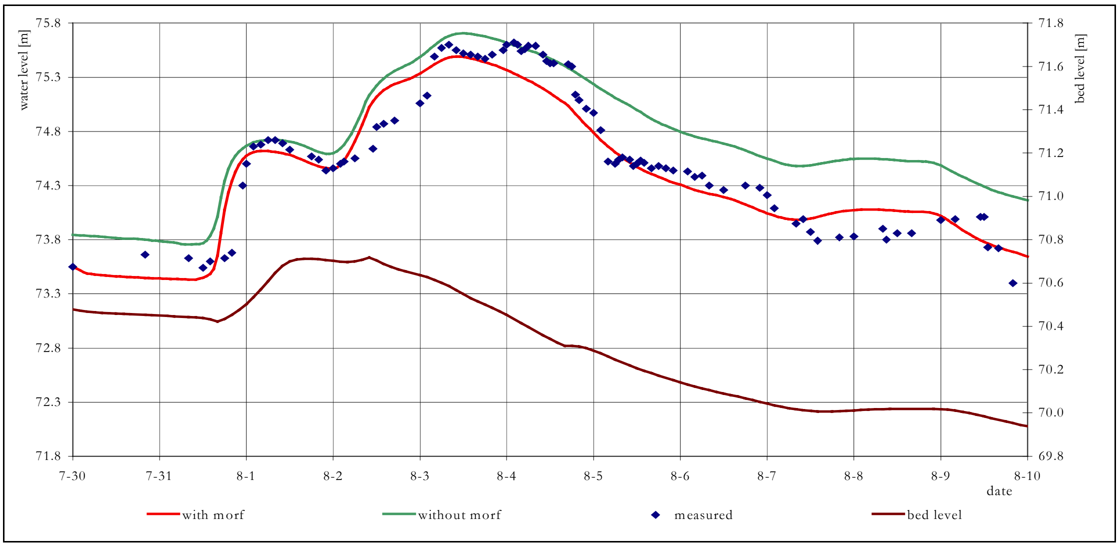


Figure 38: Influence morphology at Jiahetan

## 3.6 UNCERTANTIES IN THE MODELLING

During the model set-up a lot of assumptions have been made. Furthermore it can be expected that the data will have a certain error due to a number of reasons. The most significant assumptions and errors that have to be taken into account are described in this section. For each of them an indication is given of the expected influence on the final results.

### 3.6.1 DATA RELIABILITY

The reliability of the measured water levels and discharge could not be checked because there was no information available about the way these data were measured. In general an error of 10cm is normal for the measured water level. However the large number of measured discharges and water levels during the flood peak (around 20 per day) indicates that the expected error is smaller. Therefore an error of 5cm is estimated.

### 3.6.2 NUMBER OF CALIBRATION POINTS

In total there are four calibration points, but only three of them could be used to calibrate the water level and the discharge. The fourth one was used as boundary condition of the model. The distance between two calibration points is about one hundred kilometres. The number of calibration points, especially in between Huayuankou and Gaocun, restricts the accuracy of the model. Only with the help of some general information of the YRCC it was possible to understand the flow pattern in between the calibration points. To schematise the suspended river and the two flood peaks that occur due to this, more calibrations are needed. The lack of calibration points influences the accuracy of the discharge pattern, the discharge volume and the water level.

### 3.6.3 NUMBER OF CROSS-SECTIONS

SOBEK constructs cross-sections at the grid points via linear interpolation between the two nearest measured cross-sections. The interpolations are used to determine the cross-sections at grid points as a whole, or to determine the shape of its main channel and one or two flood plains. Interpolation between cross-sections of rather different shape may result into cross-sections at grid points whose shape may not to be realistic (SOBEK, 2000). There are only 30 cross-sections on a 300 km distance. The average distance between two cross-sections is therefore 10 km and the maximum distance is about 20 km (also see section 3.3.3). The shape of two consecutive measured cross-sections may vary a lot, because of the distance between them. Therefore it has to be expected that the interpolation is not accurate and differs from the real situation. This has a serious impact on the water levels, morphology and therefore needs attention. Especially the interpolation of the unregistered dikes is difficult. There is information about these dikes at the location the cross-sections, but none in between.

### 3.6.4 UNREGISTERED DIKES

In the measured cross-sections there are a number of self-made dikes inside the flood plains that are unspecified. The exact position, the length, height and strength of these dikes is unknown. However these dikes can have a serious impact on the flow velocity and the conveyance capacity. Second if one of these dikes breaches the flow pattern may change and consequently the conveyance capacity may suddenly increase. The uncertainties due to the unregistered dikes can influence the water levels, especially during a flood. The difference in water level can be up to 1 m. For the verification of the model assumptions were made about the expected conveyance. These assumptions were based on the comparison of the cross-sections in May and October 1982. Only the areas that changed in this period are expected to have taken part in the conveyance.

It was already mentioned that there are a lot of uncertainties about the cross-sections and the interpolation between the cross-sections. To get an impression of the influence of these uncertainties on the water level, a sensitivity analysis was made for one cross-section, viz. at Jiahetan. The cross-sectional area was calculated with the shape used for the calibration, with the removal of one of the unregistered dikes, with the removal of two unregistered dikes and finally with the removal of two unregistered dikes and an extra main channel area, as shown in Figure 39. The coloured bars in the pictures indicate the assumed width of the main channel. The colours are linked with the coloured lines in Figure 40. For each of these cross-sections the water level was calculated with the calibrated model. The first picture is the original situation.

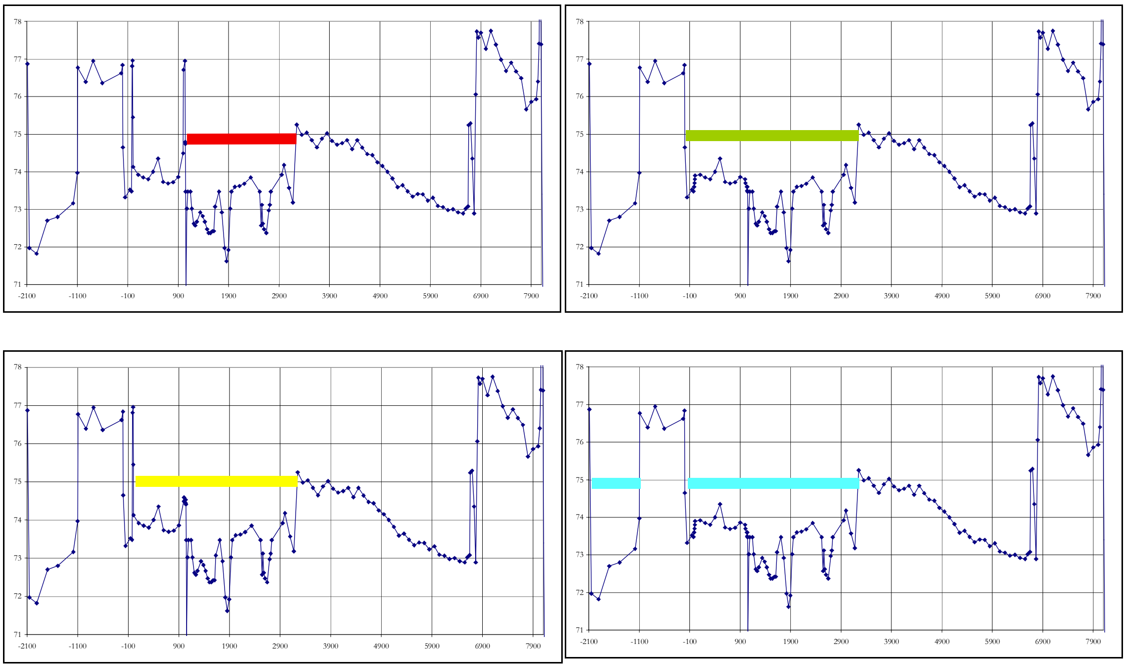

Figure 39: Cross-sectional variation

The outcome of this computation is visualised in the figure below. There is significant water level variation due to the different shape of the four cross-sections. In addition to these four cross-sections there are many other variations possible and it is difficult to say which one fits best to the real situation. The original situation fits best to the measured water level. It means that all the unregistered dikes have to be taken into account in the computations. The result of this analysis was used to determine the cross-sectional area of the other cross-sections. Each of them was based on the situation of the original situation, like in the top left panel of Figure 39.

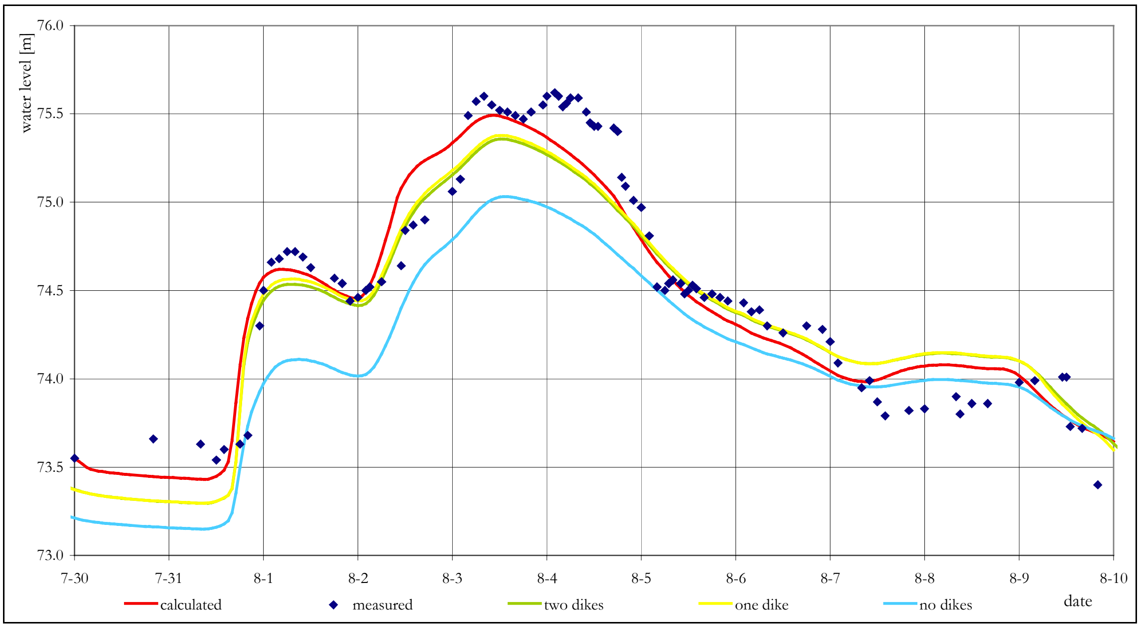


Figure 40: Relation between water level and cross-section variation at Jiahetan

### 3.6.5 GRAIN SIZES

To the author's knowledge, measurements of both the bed load and the suspended load at the same location have not been made. The grain size distribution of the bed material is analysed by sieving. In general the measured grain sizes can have an error up to 50%. Especially the suspended load can have a large error. The suspended load was used to calibrate the sediment concentration but the sediment concentration was also used to calibrate the morphodynamic part of the model. An error in the measurement of the suspended load can cause a serious error in the morphological part of the model. So the bed level variation and the erosion and deposition calculated with the model can only be used as an indication because the error in the data used to set up this model can already be 50%.

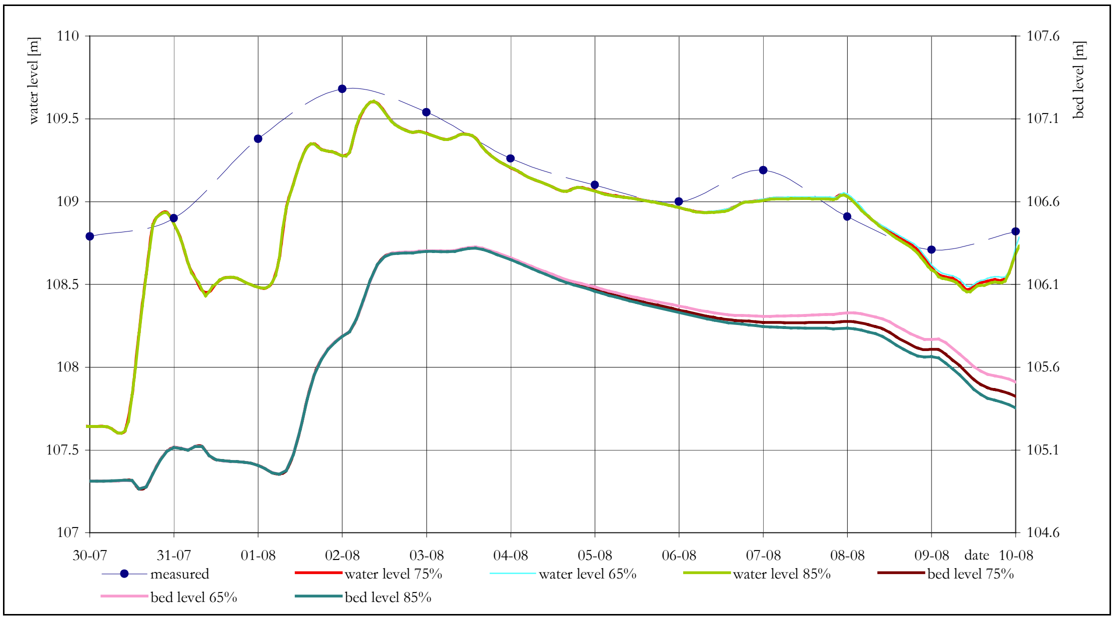


Figure 41: Influence sediment concentration variation at Peiyu

To get a better impression of the influence of the wash load variation a sensitivity analysis was carried out by varying the upstream boundary condition. For the calibration of the model a wash load of 75% was used. Two other calculations were based on a wash load of 65% and 85%. The influence of the variation was only visible at Peiyu, the first station, and the influence was rather small, see Figure 41. This may indicate that the variation of the wash load influences the bed level, but the period was too short to see a clear influence.

### 3.6.6 SEDIMENT TRANSPORT FORMULA

The sediment-transport formula was derived from a trial and error method, not through detailed research. To get a better insight into the reliability of this formula, a few factors are varied to assess their influence on the sediment transport and the water levels. The main factors of the formulae are the α, the m and the grain sizes. The first two factors are varied around the range of the calibrated model. Changing the third one, the grain sizes, would give the same results as varying the α. The results of the two variations are visualised in the following figures.

The variation in water level due to the variation of the α is rather small and not more than a few centimetres. So the α-variation seems negligible and without any influence on the water level. However the bed level change is about 0.7m and the water level change due to the bed level change is around 0.25m in Figure 37. So in this particular case the ratio between the increase in water level and the bed level change is about 1:3. In Figure 42 the difference between the bed level change due to the variation of α is around 0.2m and the water level is varying about 0.06m. This gives the same ratio as in Figure 37.

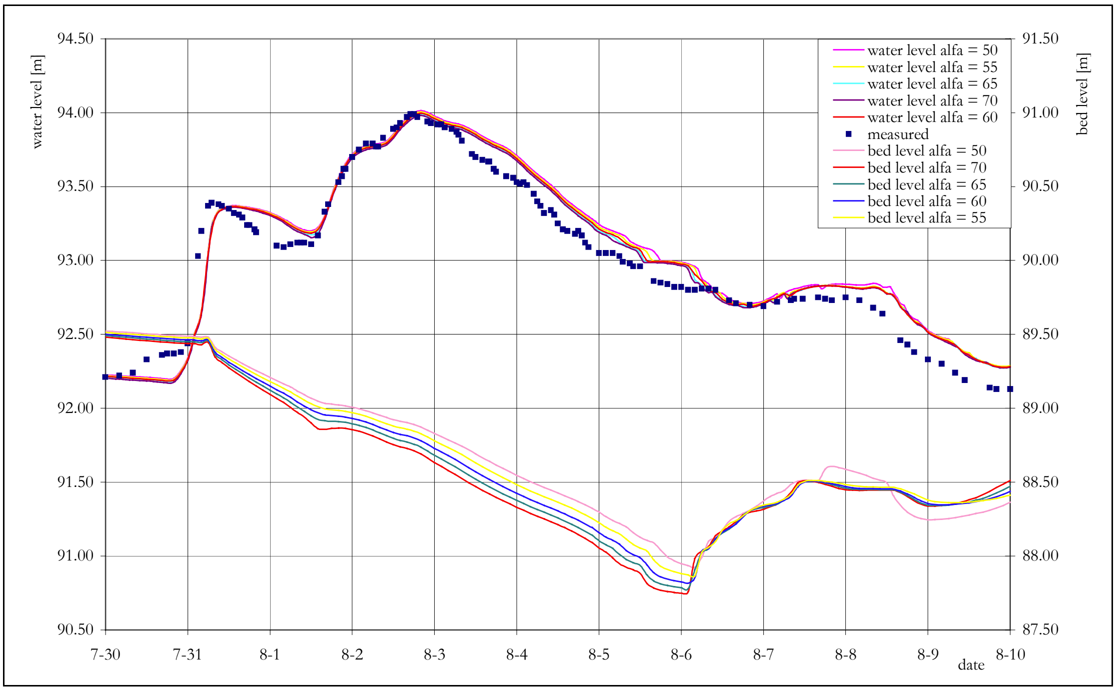


Figure 42: α-variation at Huayuankou

The m variation is the variation of the power in the sediment transport formula. For the calibrated model the m = 2.3. The variation of the m is shown in Figure 43. An increase in m causes a lower bed level and thus a lower water level. The difference in bed level change due to the m variation is about 0.2 m and the difference in water level change is about 0.05m. This is approximately the same ratio as found with the α-variation. According to this figure an increase in m change would suggest a further increase the bed level change.

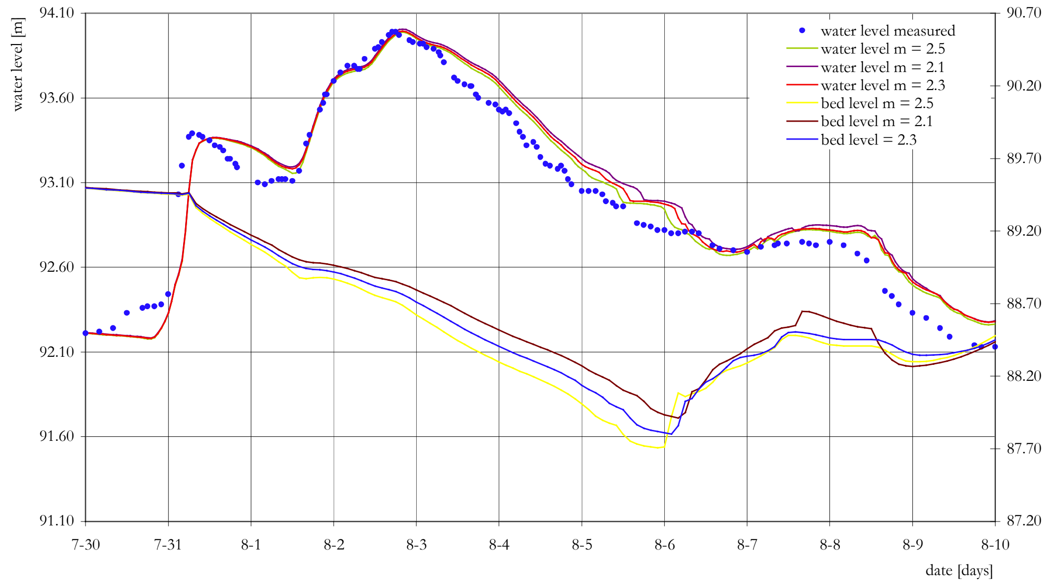


Figure 43: m-variation at Huayuankou

The conclusion is that the variation of α or m behaves the same as in the calibrated model. The ratio between the bed level change and the water level change is almost the same as for the calibrated model. The influence of the variations on the bed level and the water level is rather small.

### 3.6.7 CONCLUSIONS

There are many uncertainties in the modelling that can seriously influence the results. The main factors are the cross-sectional area, the bed level change and the number of cross-sections. Each of these factors can influence the water level in a more or less direct way. The small number of cross-sections, and especially because the lack of information about the unregistered dikes, creates a lot of uncertainties in the interpolation between the cross-sections. The real cross-sectional area is hard to determine, but has a strong influence on the water level, as shown in Figure 40. The discharge and the sediment load influence the bed level change. Before the peak flood the bottom is relatively stable, whereas there is serious erosion during the peak flood and a recovery after the peak flood (see section 3.5).

All these factors make it difficult to change the upstream boundary conditions, e.g. the discharge or the sediment load. The model is calibrated for a discharge up to 15000 $m^3s^{-1}$. Beyond this discharge the cross-sectional area is not calibrated and the unregistered dikes even have a more dominant influence. These dikes can breach or the water can overtop them. An increase of discharge or sediment load has a strong influence on the bed level and thus on the water level. The sediment transport formula applied and the uncertainties in grain sizes, especially the suspended load, make it uncertain whether the calculated bed level actually approximates reality. Therefore it is recommended to use the model with discharges up to 15000 $m^3s^{-1}$ only.

# 4 BOTTLENECK ANALYSIS & SCREENING OF MEASURES

The preliminary analysis or the second part of the development phase (Figure 44) is treated in this chapter. This part of the framework consists of a bottleneck analysis and an assessment of measures to solve the problems. An essential activity is the analysis of the WRS if present policies are continued. This activity is called the bottleneck analysis. Once the base case is defined and problems and bottlenecks are identified, individual measures are developed and screened.

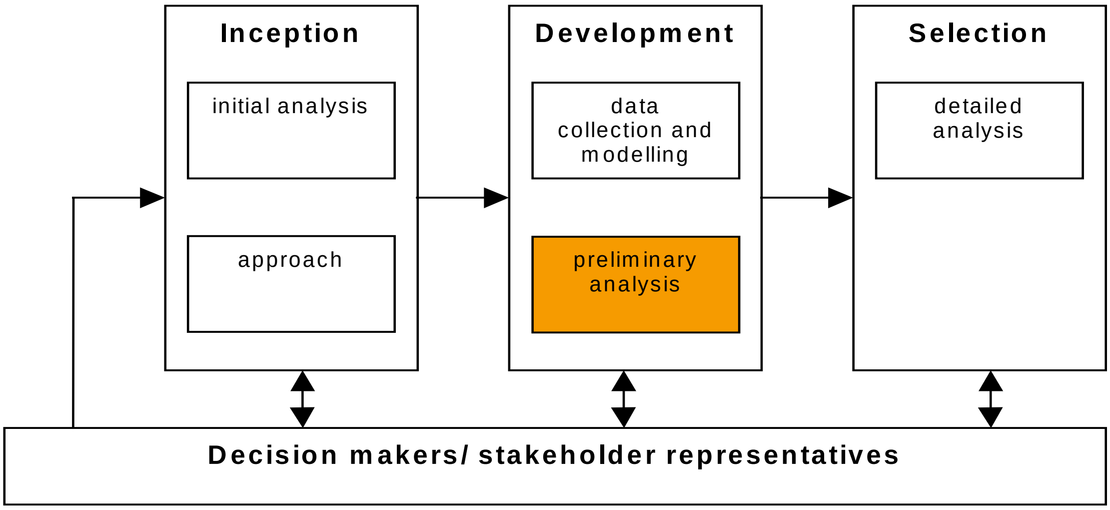


Figure 44: The second half of the development phase, the preliminary analysis

## 4.1 BOTTLENECK ANALYSIS

The point of departure for the bottleneck analysis is the base case. In this study it means before the implementation of the Xiaolangdi project. The construction of Xiaolangdi started in 1997. The base case includes e.g. the conveyance capacity, but also the bed level and slope from Xiaolangdi to Gaocun before the Xiaolangdi dam was constructed. To investigate the bottlenecks first the base case is analysed. The base case is used as a reference; in that the effects of the measures are determined by comparison with the base case situation.

### 4.1.1 BASE CASE ANALYSIS

The base case situation is plotted in Figure 45. The water- and bed level are based on the model calculations with a maximum discharge of 15000$m^3s^{-1}$. The bed level used in the calibrated model is that of 1982. The dike heights are those in 2000. This discrepancy has to be taken into account because the bed level rose in the period 1982-2000 (Table 11).

Table 11: Bed level change between 1982 -1995

| Period | Huayuankou | Jiahetan | Gaocun |
|---|---|---|---|
| 1982-1995 | 1.1 m | 0.5 m | 0.2 m |

This table shows that there was a bed level increase between 0.2 and 1.1m in the period 1982-1995. So the real difference between the water level and the dike height is smaller than the difference plotted in Figure 45. Furthermore the calculated water level is based on a maximum discharge of 15000m$^3$s$^{-1}$ whereas the design discharge is 22000m$^3$s$^{-1}$. It would have been better to compute with the design discharge but due to a number of reasons this was impossible (see section 3.6.7).

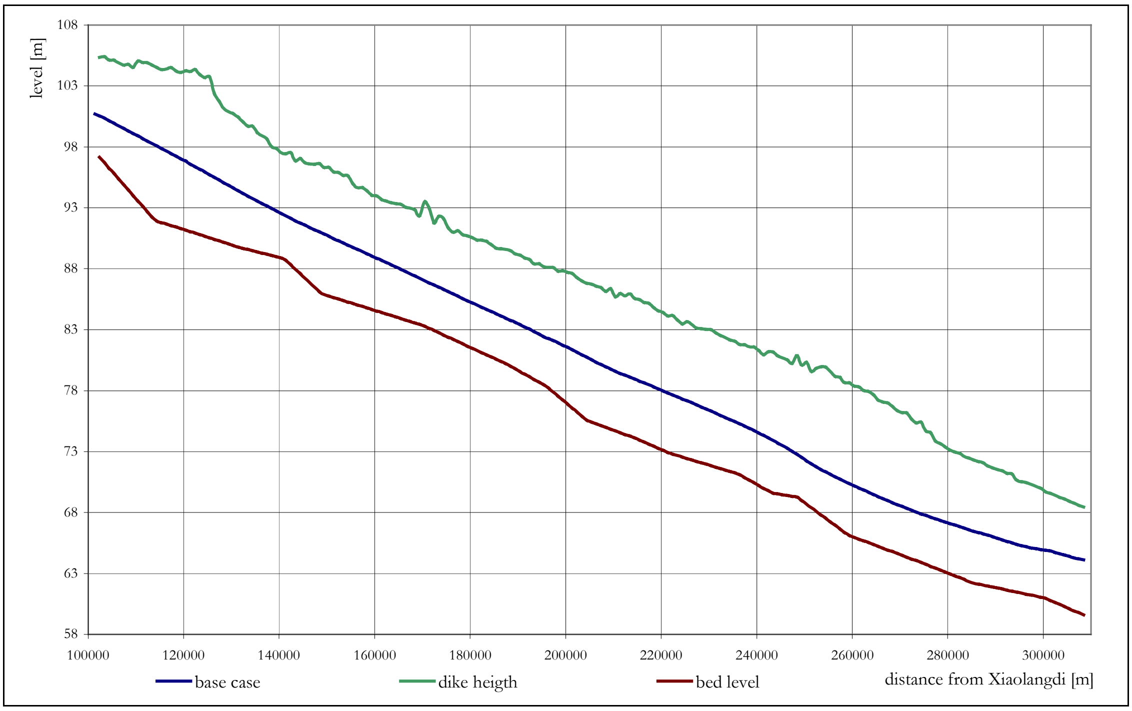


Figure 45: Base situation for the water level, bottom level and dike height

The base case shows that the difference between the maximum water level and the dike height is at least 3 m, so the current situation meets the requirements of safety (also see section 2.2). Even when taking into account the bed level rise in the period 1982-2000 and the design discharge, the current situation can be expected to meet the requirements of safety. The only remark is that the current safety level is based on a flood with a probability of 1/60 per year, so very low compared to the Dutch situation.

### 4.1.2 BOTTLENECK ANALYSIS

The objective of the bottleneck analysis is to show the bottlenecks in the WRS. In this case the main bottleneck is the continuous bed level rise. In the last fifty years the bed level rise was about 2 m. The key question is: will the river tilt further?

The study of Kriele & de Vries showed that the propagation of the river mouth results in an increasing water and bed level in the lower reach. The rising water level causes a change of the flow path every 10 years, resulting in a shortening of the flow path, which causes a temporary lowering of the water and bed level. The relaxation length belonging to this 10 years period is about 200 km. The study area is located at least 500 km from the river mouth. This indicates that there is not a direct influence of the shift of the erosion base on the bed level in the study area.

The reason for the bed level rise is the deposition of sediment due to the lack of sufficient flow. This process of continuous deposition of sediment is expected to continue at least with the same speed, because of the decreasing annual inflow. Unfortunately it was impossible to model this expected bed level rise. The base case showed that the current situation is under control but the bottleneck analysis shows that the design flood discharge decreases due to the bed level rise.

## 4.2 THE HISTORY IN COPING WITH FLOODS

In this section the history of river management and especially flood control of the Lower Rhine River in the Netherlands is described and compared with the lower reach of the Yellow River in China. The objective is to determine the similarities and the differences in managing these rivers and especially the way the people cope with floods.

### 4.2.1 THE YELLOW RIVER HISTORY IN COPING WITH FLOODS

This section is an abstract of a brochure named "A general introduction of the Yellow River" and issued in 1999 by the YRCC.

The Yellow River has a long history in river management, due to frequent flood disasters that happened in the history. Jia Rang, a person who lived 2000 years ago had put forward "three Measures on River Management", which was the earliest document on river management policies in China. Wang Jing of East Han Dynasty (app. 1800 years ago) led hundreds of thousands people to build about 500 km of canals and dykes.

In historical times, normally, there were no great shifts of the river channel in the upper and middle reaches. Only the river channel on the lower reach shifted frequently. Taking Zhengzhou city as a pivot, it shifted to Tianjing in the North, and reached Yangtze River and Huaihe River in the south. Eight times a major shift took place of the lower reach of the Yellow River. The first major shift occurred in the fifth year of the Zhouding Empire (602 BC) according to the historical record.


Figure 46: Yellow River channel shift in the past. (Source: YRCC, 2001)

The last dike breach in the lower reach of the Yellow River was closed in 1946. After bringing the river back to its original course, the YRCC, which had adopted the policy of "keeping wide river sections and strengthening embankments", built flood detention basins and conducted protection works using the historic experience. Along with the construction and development of soil conservation works in the upper and middle reaches and reservoirs built in the main river and its tributaries, a system of flood control engineering works “retaining water at the upper stream, discharging at the downstream and retarding at detention basins on the both banks” has been formed. This changed the situation of only relying on the dykes to a situation in which no dyke breaches during summer and autumn floods have occurred during the last 52 years.

In 1958 a peak discharge of 22,300 $m^3s^{-1}$ was measured at Huayuankou. This flood was formed mainly because of the heavy rainfall that occurred in the trunk and tributaries area below Sanmenxia. The peak discharge had the characteristics of a rapidly rising high water level with a low sediment concentration and a long duration (YRCC, 2001). Based on this 1958 flood the short-term mission of flood-control is formulated: to guarantee that the main dyke does not breach under the flood peak of 22,000 $m^3s^{-1}$ observed at Huayuankou (YRCC, 2001). The policy adopted by the YRCC to guarantee these design criteria is to “barrage in the upstream, discharge in the downstream and retard in both banks”.

### 4.2.2 THE RHINE RIVER HISTORY IN COPING WITH FLOODS

The Netherlands is a low-lying country, situated in the delta of three international rivers: the Rhine, the Meuse and the Scheldt. A large part of country lies below sea level or below the high-water level of the major rivers. In history, flood risk management has always been focussed on the prevention of floods. Before 1000 AD the part of the Rhine river flowing through the Netherlands was regularly flooded. The people adapted their life style to the river regime and considered floods to be part of their normal life. Around 1000 AD the people started to build dikes and around 1300 AD an almost continuous chain of dikes was formed. After each flood dikes were repaired and raised until the highest occurred level plus 0.5m freeboard. These higher dikes increased the feeling of safety of the inhabitants living in the flood prone areas, which resulted in new investments in the area. The increased value of the area meant also a higher potential damage and thus a growing need for more protection. In this way a continuous spiral of investing, need for more protection, improving of dikes, investments etc. was formed (De Bruijn and den Heijer, 2001).

Figure 47:The area of the Netherlands threatened by floods (Source: de Bruijn, 2000)

After the severe coastal flooding in 1953, triggering the well-known 'Delta Project', major investments in protection measures were made. At the same time this flood incurred new regulations for safety, not only for the coast but also for the rivers. Previously, dike heights were based on the maximum recorded water level, but after 1953 a more scientific approach was used. The optimum level of safety was defined via the accepted probability of flooding for the different areas in the Netherlands. To be able to implement this new norm, it was simplified to the requirement that the dike level should exceed the water level related to a discharge with a given return time. For the inland river reaches, this is the discharge with a probability of occurrence of 1/1250 per year (the design discharge). Flooding by other causes than overtopping of dikes and uncertainties in nature and in the calculations were considered by adding 0.5 m freeboard to the required height. Every five years the design discharge is calculated anew, based on the latest discharge statistics and the actual state of the river (De Bruijn and Klijn, 2001).

### 4.2.3 CONCLUSIONS

There are a number of similarities between the history of the Rhine River and the Yellow River;

- The part of the Rhine River flowing through the Netherlands and the lower reach of the Yellow River are both situated in a delta and they both have little interaction with the surrounding area (few tributaries).
- Management of the rivers started about twenty-five centuries ago and their first objective was protection against flooding;
- The discharge pattern and the peak discharge are comparable;
- For both rivers dikes are used to protect against flooding;
- Nowadays these dikes are still an important part of the flood defence system in either river;
- Between twenty centuries ago and today dikes have been raised and strengthened after every flood;
- For centuries dikes have been the main and actually the only method of flood defence in both countries.

The most important physical difference is the sediment concentration and especially its impact on the lower reach of the Yellow River. Another difference is that China adopted the policy to widen the river sections and to build detention basins since 1946, while in 1953 the Netherlands changed the way of determining the design flood level to a more scientific approach.

Overall it can be concluded that there are a lot of similarities between the lower reach of the Yellow River and the Rhine River. There are similarities both in the river system, the main problems and the way they have been managed so far. During the last fifty years the attitude in managing the rivers changed. Therefore it seems interesting to compare the current management strategies of the rivers, so as to figure out whether there can be cross-fertilisation..

## 4.3 COMPARISON OF FLOOD MANAGEMENT IN THE RHINE RIVER AND THE YELLOW RIVER

In this section the actual flood management strategies for both the Lower Rhine River and the lower reach of the Yellow River are described and compared. Subsequently the expected strategies in the near future are considered.

### 4.3.1 FLOOD MANAGEMENT STRATEGY FOR THE LOWER YELLOW RIVER

#### Actual flood management strategy

At this moment the design level of the dikes along the branches of the lower reach of the Yellow River is based on a discharge of 22000 $m^3s^{-1}$ with a probability of occurrence of 1/60 per year. The ongoing sedimentation in the lower reach has increased the bed level through the years and the difference between the actual flood level and the design flood level becomes larger and larger. For example, the 1982 flood, with a peak discharge of 15,300 $m^3s^{-1}$ was the second major flood since the foundation of the PRC. Compared with the 1958 flood of 22,300 $m^3s^{-1}$ the discharge was 7,000$m^3s^{-1}$ less. Yet, the water level between Huayuankou and Gaocun was about one meter higher, mainly due to the aggradation of the channel (YRCC, 2001). To be able to accommodate the design discharge, one faces continued dike raising. Moreover, the population density in the areas around the lower reach of the Yellow River has become one of the highest of the country. As a consequence, flood control becomes even more important. To stop the process of continuous dike raising the YRCC decided to construct the Xiaolangdi dam to improve the flood control and to increase the safety level. It is expected that the Xiaolangdi reservoir will play a significant role in flood control and sediment reduction in the lower reach. The design flood discharge of the channel will increase and be able to cope with a flood with a probability of 1/1000 per year (Li, 2001). In this way it is expected that flood control in the lower reach of the Yellow River will improve for at least twenty years. But this is a short-term solution and designed from an engineering perspective. It does not take into account all the aspects and functions of the lower reach, such as like nature and environment.

According to an engineer of the design institute of the YRCC there are also negative effects of the implementation of the Xiaolangdi reservoir. There are still flood control problems in the lower reach, although many people seem to think they are over now. Dike breaches are still possible, due to under scouring of the toe of the dike. Moreover, during a major flood Xiaolangdi will discharge between 8000 and 10000 $m^3s^{-1}$, which is the same as the peak discharge measured at Xiaolangdi during the 1982 flood.

#### Prospective flood management strategy

The objective of the YRCC in the near future (year 2010) is to improve the engineering system and non-engineering measures of flood control. In order to prevent that a flood with a discharge of 22,000 $m^3s^{-1}$ at Huayuankou will occur, a water and sediment regulation system of the Yellow River will be implemented that controls floods effectively and realises the objective of long-time safety. In order to realise the above-mentioned aims, the policy on “retaining the flood in the upstream and discharging in the downstream and retarding floods in detention basins on both banks” should be implemented consistently. The flood management has to be combined with sediment management following overall policy of “retaining, discharging, warping, regulating and dredging”. The two policies should be combined, so as to form a system of flood control and sediment reduction to gradually realise the purpose of long-term safety of the Yellow River (Li, 2001).

### 4.3.2 FLOOD MANAGEMENT STRATEGY FOR THE LOWER RHINE RIVER

#### Actual flood management strategy

The management of the Lower Rhine River has changed during the last fifty years. Instead of only focussing on the river and flood control, the policy changed to a more overall and integrated view. This policy is still in an early stage of development, but the way of thinking gives the opportunity to integrate all the aspects of the river, its functions and the interests of people that rely on it, like farmers and industry. Secondly this approach enables to look for solutions in a wider scope than technically. Thirdly the growing population and the related property, also inside the basin, creates more damage in case of flooding and therefore asks for a changing approach (also see Figure 48).

Due to the flood events of 1993 and 1995, which added information to the extreme discharge statistics, the design discharge ends up being higher than it was prior to these events. At this moment the design height of the dikes along the Rhine River is based on a discharge of 15,000 $m^3s^{-1}$ with a probability of 1/1250 per year. At the end of 2001 the design discharge raised to 16000 $m^3s^{-1}$. Without further measures, this also means higher water levels. But plans were developed to maintain the safety level without further raising the dikes. Due to the expected climate change, the design discharge will probably further increase in the long run to 18000 $m^3s^{-1}$. At the same time, the sea level is expected to rise due to the climate change, causing backwater effects in the estuaries and rivers.

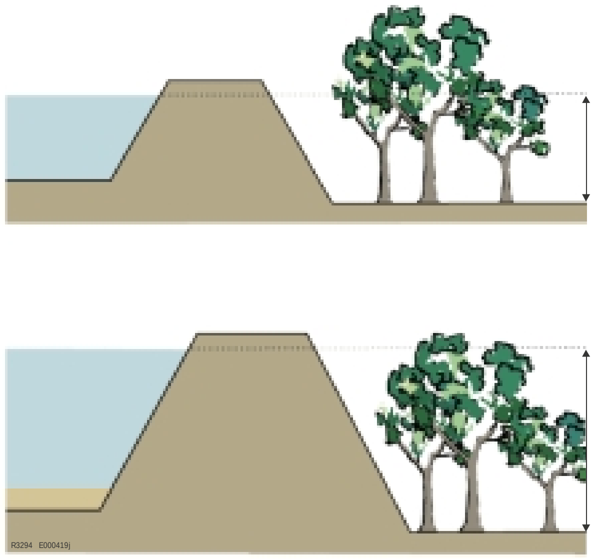

Figure 48: Continuous dike raising creates more damage in case of flooding (Source Riza et al., 2001)

To breach the spiral of ongoing dike raising, the Dutch Government has recently decided to develop and implement a new flood protection policy called 'Room for the River'. The challenge is to create and execute measures despite the higher design discharge, which may prevent a new round of dike raising. This means that measures are sought that lead to a decrease of the design water level. (RIZA et al. , 2001)

### Room for the River policy

In preparation of the policy 'Room for the River' the exploratory study 'Room for the Rhine branches' was carried out between 1998 and 2000. The objective of this study was to advise the Government in which way 16,000 $m^3s^{-1}$ could safely be conveyed without raising dikes. The 'Room for the River' policy was an outcome of this project and adopted by the Dutch government in the year 2000 for the overall river management in the Netherlands. The objective of this policy is to prevent dike strengthening as much as possible by creating more space for the river, such that water levels will not rise as a consequence of higher design discharges. There are two ways to prevent the water levels from becoming higher as the discharge increases. Storage of river water in detention areas along the Rhine Branches leads to a lowering of the discharge peak and hence the water levels downstream of the measure.

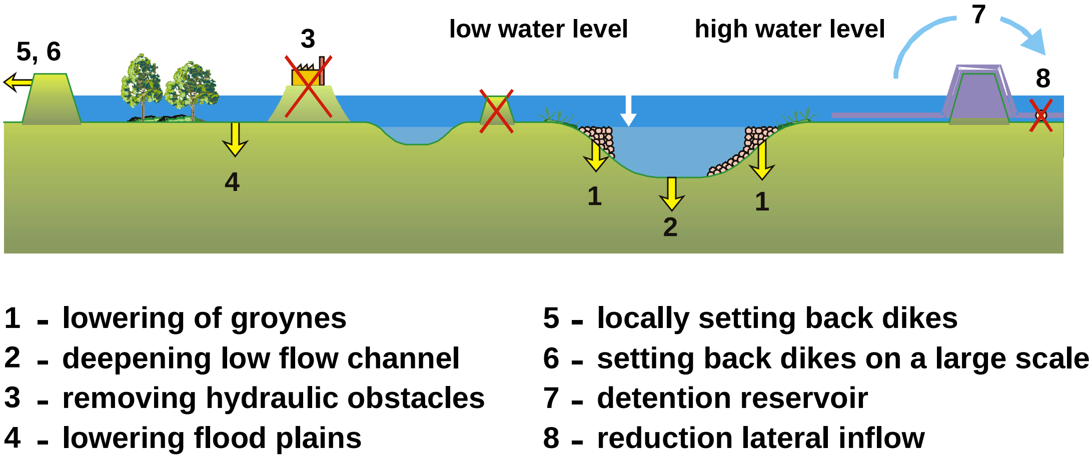


Figure 49: Room for the river measures (Source: RIZA et al. 2001)

The second category of measures increases the discharge capacity of the river and thus reduces the water levels upstream of the measure. Examples include the removal of obstacles in the floodplain, dredging and setting back of the dikes. For an overview of the measures put forward in the Room for the River policy, see Figure 49. With discharge increasing measures, it is not only important which water level decrease is reached in terms of height, but also the distance over which its influence extends upstream (RIZA et al., 2001).

**Prospective flood management strategy**

Since the consequences of a dike breach might be disastrous, attention has been focussed on the prevention of floods. The drainage of the protected area and the absence of floods caused the area to subside. As a result, nowadays, large areas of the Netherlands lay below sea level or below the level of the flood plains. On the other hand, the level of the flood plains has increased. Frequent flooding combined with a low velocity in these plains resulted in the deposition of sediment and hence a significant increase of the level of these plains. When a dike breaches or overflows, water will enter relatively low-lying areas where many people live and work. Because of this the protected areas know only two flooding states: non-flooded or catastrophically flooded. As a result, public interest has traditionally been in prevention of floods rather than in the impacts of possible floods. This attitude is reflected in the measures taken so far and the studies carried out (probability of dike failure, or exceedence of dike height, instead of potential damage studies) (De Bruijn and den Heijer, 2001).

In the near future a risk-based flood protection policy in the Netherlands may be implemented. This is not entirely obvious, because it requires a political discussion about a different safety norm system. The present system, based on equity of probability exceedence of the flood defence system, will no longer be adequate. The flooding risk is defined as the probability of an event (extreme river discharges, storm, combination of these two) multiplied by the consequences of this event (damage, victims). The consequences can differ, depending on the nature of the threat (sea or fresh river water; short or long lasting; expected or unexpected) and the features of the area (depth, buildings, industry, and population). In case of rapid inundation and large depths, many victims have to be expected. During the coastal flooding in 1953 it was observed that most casualties occurred in the small polders because the water level rised relatively quick. Escape possibilities and early warning can play an important mitigating role. According to a risk-based approach dike sections can be dimensioned less stringently if the consequences of a flood are less critical. This approach also offers the possibility of introducing other flood protection measures than raising dikes (NEDECO-WL│Delft Hydraulics, 2001).

### 4.3.3 CONCLUSIONS

The flood management strategies for the lower reaches for both the Rhine and the Yellow River are based on a design discharge. The design discharge for the Lower Rhine River is 16,000 $m^3s^{-1}$, with a probability of 1/1250 per year and the design discharge for the lower reach of the Yellow River is 22,000 $m^3s^{-1}$ with a probability of 1/60 per year (without taking into account the influence of Xiaolangdi). For both rivers the actual discharge capacity does not meet the design level. The actual design level of the Lower Rhine River is 15,000 $m^3s^{-1}$ and the actual design level of the lower reach of the Yellow River is less than 15,000 $m^3s^{-1}$. Therefore both countries started to work on enlarging the actual discharge capacity, but the policies to achieve this are different. The Netherlands attempt to break the spiral of continuous dike raising and want to create room for the river and include spatial planning within the river management policy. China constructed the Xiaolangdi reservoir just upstream of the lower reach of the Yellow River in order to improve the flood control.

The long-term flood management strategies differ even more than the short-term ones. The Yellow River long-term strategy focuses on an engineering approach, raising and strengthening the 1300 km of levees. In addition the focus is on constructing dams like the Sanmenxia and more recent the Xiaolangdi, in order to stop the accretion of the main channel for at least twenty years and to improve flood control for the downstream area of the dam. The Netherlands long-term flood management focuses on a change from a water level-based approach to a risk-based flood protection policy. This means that the flood management strategy will no longer focus only on exceedence probability but also on inundation probability and potential damage.

Overall it seems reasonable to say that the traditional methods are not able to create a sustainable and safe WRS for the lower reach of the Yellow River and the flood-prone areas around it. Therefore it can be interesting to look at the river and its management from a different point of view, in order to find other measures and strategies to improve flood control. There are many ways to do this. In the previous section it was recommended to compare the actual management strategies of the rivers to figure out if we can learn from each other. Therefore it is interesting to investigate the possibility of learning of the “Room for the River” policy in order to improve the flood control of the lower reach of the Yellow River. Especially because this approach integrates functions, focuses on the long term and takes into account the damage in case a flood would occur. This approach may be able to contribute to a sustainable Yellow River in the long run.

## 4.4 PRELIMINARY FLOOD MANAGEMENT MEASURES

In this section the measures out of the “Room for the river” policy are adapted to the lower reach of the Yellow River, in order to suggest alternative ways of improving flood control. The ‘Room for the River” policy as described in section 4.3.1 has brought up a number of new and interesting measures, though not all of them can be adapted to the Yellow River. The lowering of groins is impossible because in the Yellow River groins don’t exist. Most other measures can be adapted to the situation in the lower reach of the Yellow River and the result is a set of suggested approaches improving flood control. The way of adapting these measures is described in this section. Their influence on the water levels is calculated and analysed for the reach between Huayuankou and Gaocun. This section is analysed because it is most important in terms of flood control.

The calculation is carried out with the 1D-model. The peak flood of 1982 is used to calculate the water levels. The reason to use this flood instead of the design flood is based on the conclusions of the modelling (section 3.6.7). In each of the cases the results of the base case are compared with the results of the case with the measure. The maximum water levels are compared and the differences are plotted in the figures.

### 4.4.1 FLOOD PLAIN WIDENING

The width between dikes in the project area varies between 5 and 16 km (Figure 50). In the narrow sections the variation is expected to influence the flood conveyance in a negative way. Therefore it can be interesting to set back the dikes at the narrow places to increase the flood conveyance and finally to drop the water levels. The measure can only be executed downstream of Huayuankou. Upstream of Huayuankou (in Figure 50 up to 130 km downstream of Xiaolangdi) the river flows through a valley that is surrounded by hills and mountains, downstream of Huayuankou the river is surrounded by dikes. For this measure the minimum width between the dikes is 9 km. This is illustrated by the blue line in Figure 50. The red line is the new dike that fulfils the requirement of a minimum width of 9 km. In total 170 km of new dikes have to be built, 85 km on either side. In addition land acquisition is necessary. The total area is about 800 km², 400 km² on each side. The number of people living in this area and having to be relocated or evacuated in case of emergency is 300000.

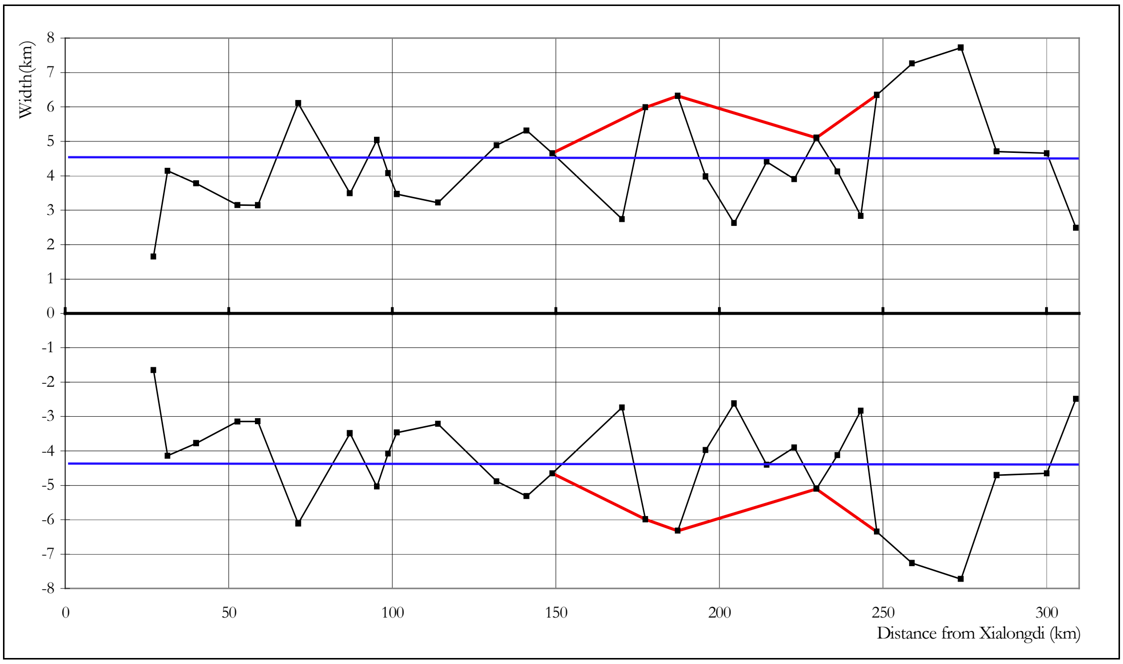


Figure 50: Visualisation of the measure flood plain widening

The maximum water level is calculated for the base case and for the case with the flood plain widening. The difference in maximum water level is plotted in Figure 51.

The computation with the flood plain widening is carried out in two ways, with and without the morphological module. The same is done for the base case. The computation without the morphological module shows a maximum water level drop of 55 cm, see Figure 51. The computation with the morphodynamic model gives the same type of results. The main water level drop is found in the section of the flood plain widening, but moreover the influence is also extended upstream and downstream of this section. Upstream in a positive sense, in that the water level drops due to the measure, but downstream in a negative sense: the water level rises due to the measure. The maximum water level drop is 42 cm and the average water difference between the base case and the measure is about 20 cm for 120 km (130-250 km downstream of Xiaolangdi).

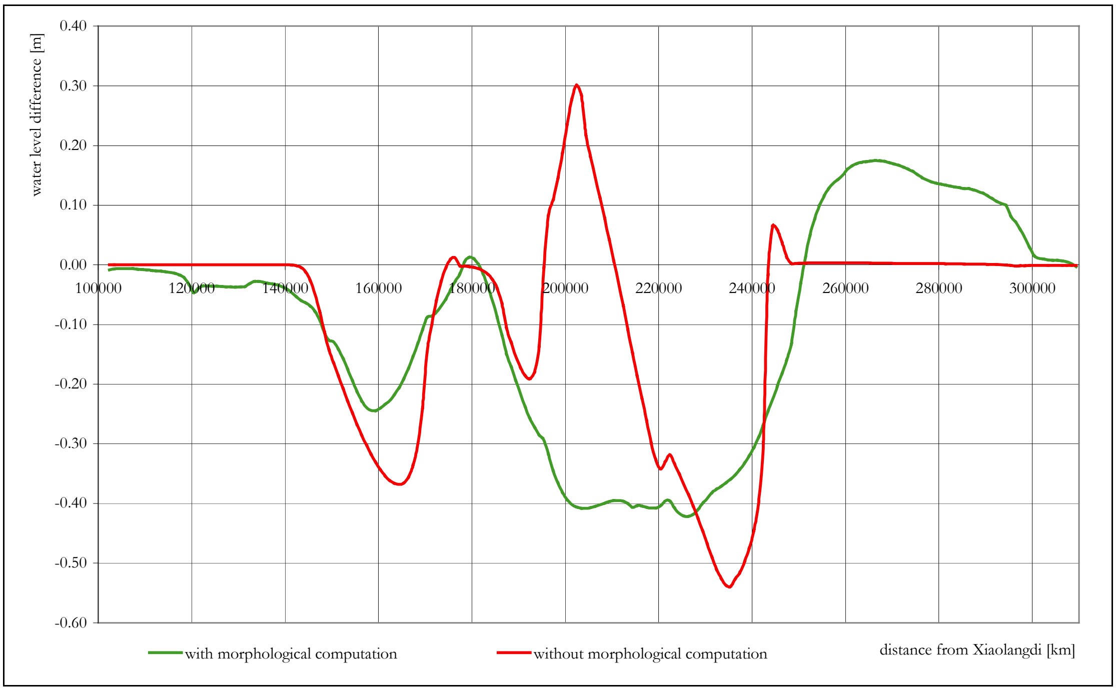


Figure 51: Influence measure flood plain widening

The reason for the negative effect at the downstream side is illustrated with the help of Figure 52. Downstream of the flood plain widening there are two channels modelled (also see section 3.3.1). The main channel is taken into account in terms of water level because the flood plains (side channel in the model) are lower than the main channel. Figure 52 shows the bed level and the water level at the bifurcation point. The bed level in the computation with the measure is lower than that in the base case. The same goes for the water level. As a consequence less water is diverted to the side channel (flood plains) and most of the water flows through the main channel, which causes a higher water level than in the base case. So it seems that the water level rise in this section is mainly caused by the way of modelling of this section, but this need to be investigated in further detail.

The computation with and without morphology shows ,once more, that it is important to use a morphodynamic model, not only a hydrodynamic model. Although the qualitative results are comparable, there are some significant differences and the quantitative results differ a lot. This also indicates that it is important to investigate the long-term morphological results and not only the short-term effects.

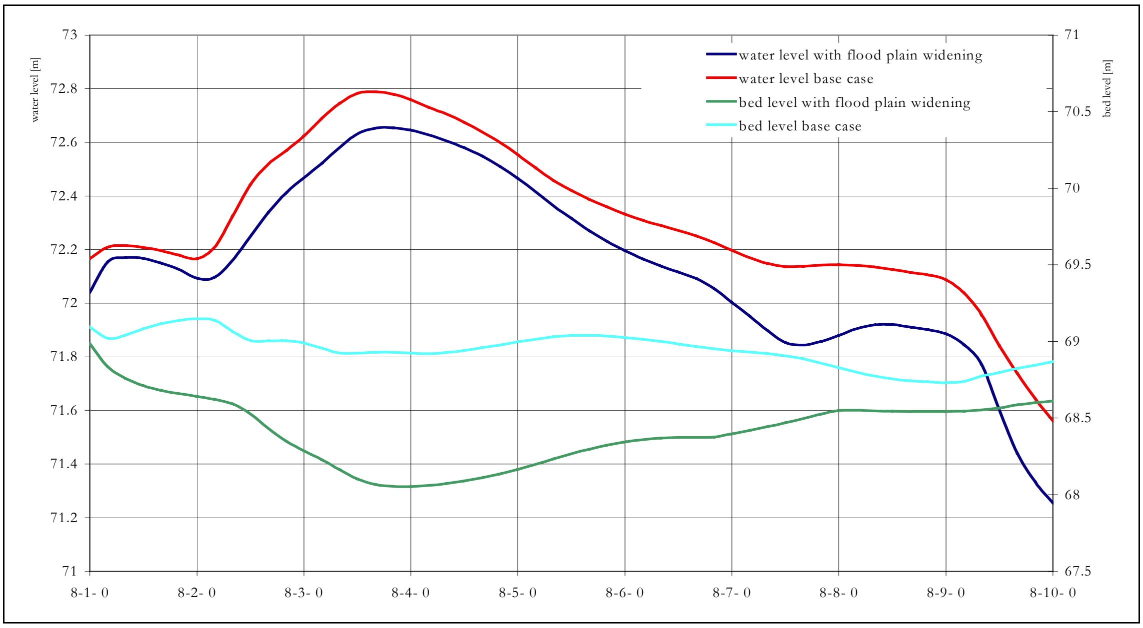


Figure 52: Bed- and water level variation at 223 km from Xiaolangdi

### 4.4.2 REMOVAL OF UNREGISTERED DIKES

In the flood plain, especially between Huayuankou and Gaocun there are a number of unregistered dikes. These dikes seriously influence the flood conveyance and the water level. The strength, height and length of these dikes are unknown, except for the information provided by the cross-sections. These dikes only influence the water motion at peak discharges, not during the low discharges. On the flood plains between Huayuankou and Jiahetan live about 1.1 million people. Most of them are farmers who cultivate crops on the flood plains and have built dikes in the flood plain to protect their crops. To resettle these people can be interesting in many ways. First of all to minimise the risk of casualties. Second the flood conveyance will increase without all these unregistered dikes. Third the roughness may of the flood plain will lower because a lot of houses and roads can be removed, although it may be possible that these flood plains will be replaced by vegetation. This would increase the roughness of the flood plains. The pictures in Figure 53 show the cross-sections between 130 and 180 km downstream of Xiaolangdi. In each of these cross-sections unregistered dikes are found. The red lines indicate the unregistered dikes. The removal of these dikes will increase the flood conveyance and lower the water levels.

The measure that is taken in this study is the removal of all unregistered dikes between Huayuankou and Jiahetan (130-235 km downstream of Xiaolangdi). It is assumed that the unregistered dikes are found everywhere between Huayuankou and Jiahetan. In general there are two unregistered dikes on each cross-section. The average area of these dikes is about $10m^2$. The total volume of sand that was removed is 2.1 million $m^3$, which is 1.05 million $m^3$ for each of the dikes. The removal of these dikes also implies the evacuation of the people living on the flood plains during a flood or even the resettlement of the people. Between Huayuankou and Jiahetan live 1.1 million people on the flood plains.

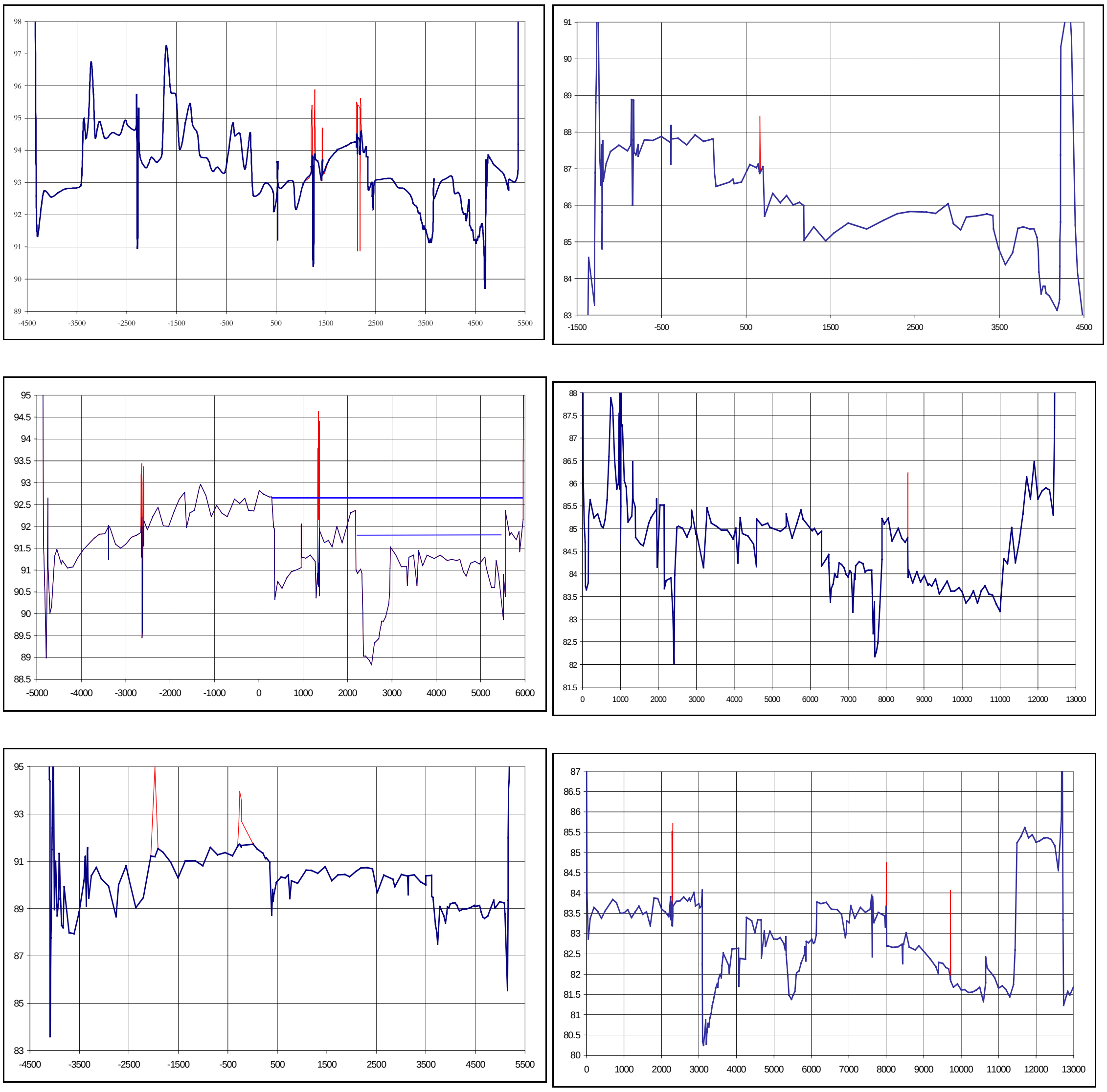

Figure 53: The locations of the unregistered dikes

The influence of the measure is plotted in Figure 54. The graph shows that the water level drops through the removal of the dikes, although the difference is small. The removal of these dikes was only carried out between 130 and 235 km downstream of Xiaolangdi, but the influence is also visible upstream and downstream of this reach. The maximum water level drop is 25 cm, with an average around 10 cm for 140 km (110-250 km downstream of Xiaolangdi).The downstream effect was not expected, but the same kind of effects as mentioned for the flood plain widening play a role in higher water levels downstream of the measure. These effects are due to the way of modelling in combination with the morphology.

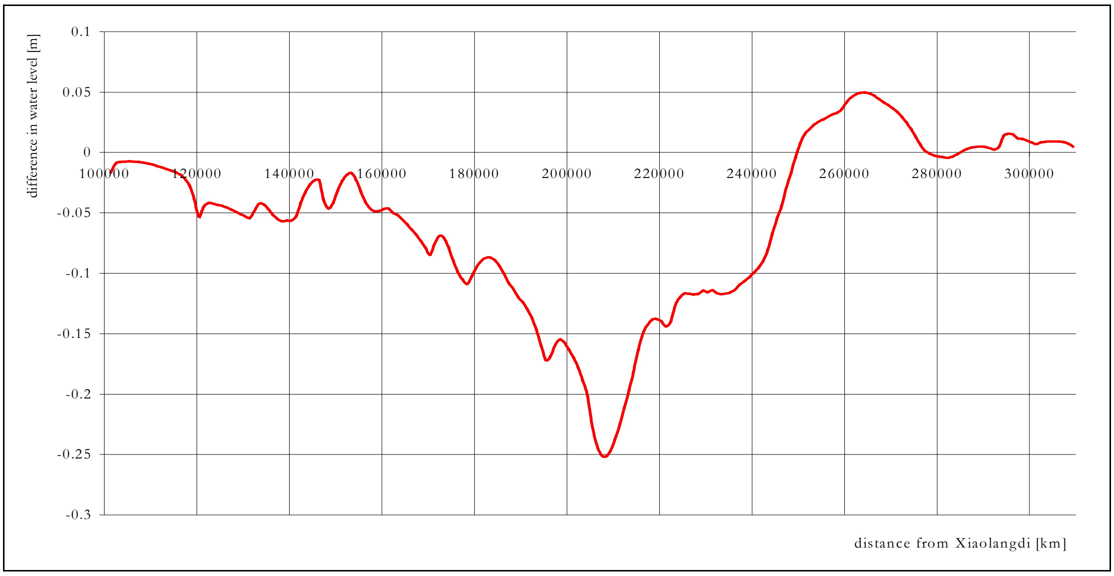


Figure 54: Influence measure removal unregistered dikes

### 4.4.3 DETENTION

Beijindi is the most upstream detention basin and one of the most important of the YRCC. At the moment 1.5 million people live in the detention area. The total capacity of this basin is 2 billion $m^3$. The objective of the measure is to determine the effect in this basin on the downstream water levels. The current inlet is situated a few kilometres downstream of Jiahetan. The effect of timely detention during a peak flood is simulated with the model. In this case the flood peak is topped at 11000 $m^3s^{-1}$ (Figure 55), by diverting the excess discharge into the detention basin. The total amount of water stored is less than 0.5 billion $m^3$, which is only 25% of the capacity. Given the number of people living inside this basin, at least a flood early warning system and an evacuation plan are needed. But even with a good evacuation plan, the risk of casualties and damage is very high. Therefore it is wiser to relocate a large number of the people living in this detention basin. It is recommended to resettle at least 1 million people. The influence of the measure detention is plotted in Figure 56.

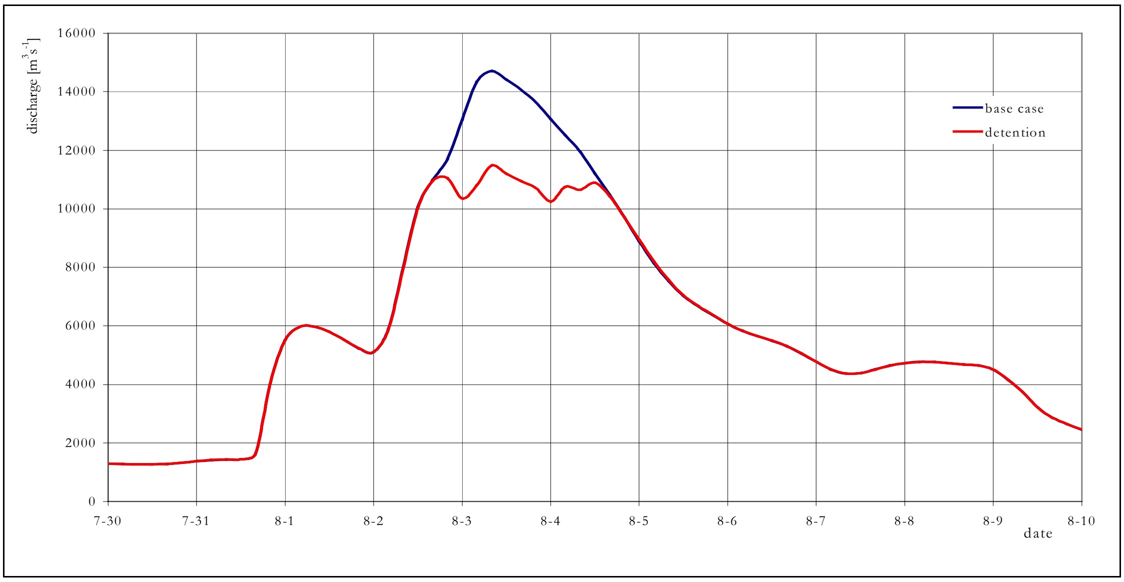


Figure 55: Flood peak at detention basin

The water level drops downstream of the withdrawal point, see also Figure 56. Around 240 km downstream of Xiaolangdi the water level drop decreases and increases sharply. The reason is that only water is withdrawn whereas the water is full of sediment. Downstream of the withdrawal point the sediment deposits and creates a sandbank. The blue line belongs to the withdrawal up to 11000 $m^3s^{-1}$. The red line belongs to a withdrawal up to 9000 $m^3s^{-1}$ and is added to show the influence of changing the measure.

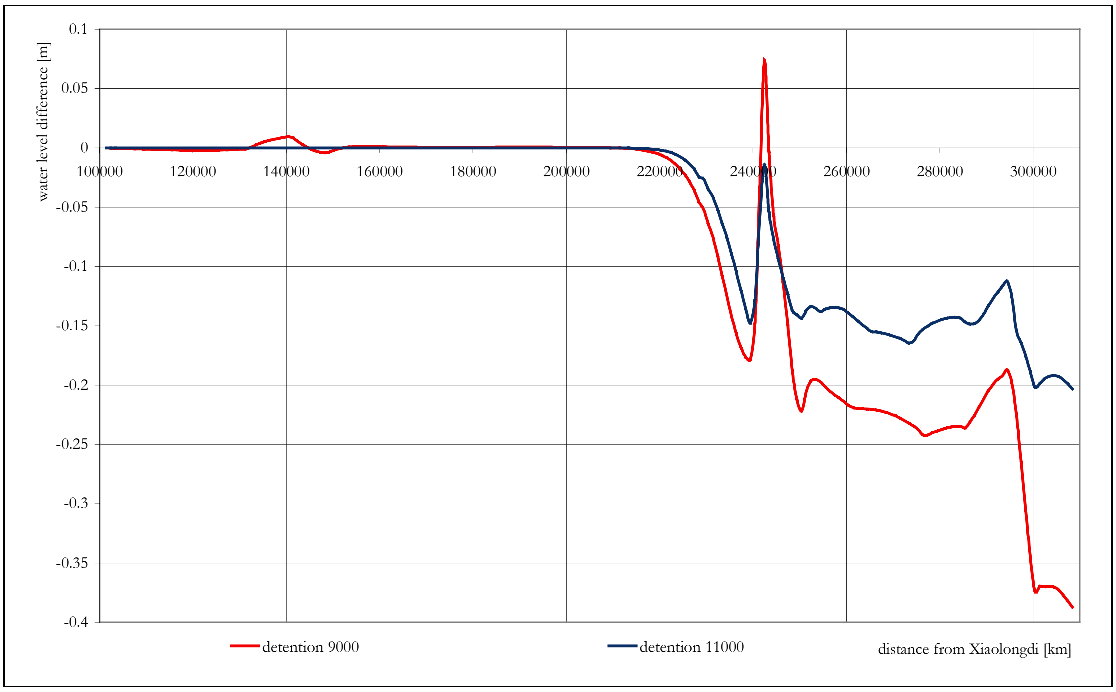


Figure 56: Influence measure detention

The use of the detention basin has a positive effect on the downstream water level. The maximum water level drop is almost 0.2 m and the average difference is about 0.1 m. The flood peak could also have been topped at a lower discharge because only 25% of the detention basin is used. This would have resulted in an increase in water level drop.

### 4.4.4 DREDGING

It is interesting to determine the possibility to control the deposition in the lower reach of the Yellow River by maintenance dredging, for example in the main channel. The idea behind the measure is to improve the discharge capacity in the main. In addition to the volume to be dredged, the effect of the dredging on the water level is important. Seven continuous dredging locations are specified in the section Huayuankou-Gaocun (see Table 12). The criterion is that the bed level may not rise during the calculation period. Figure 57 shows the base case and the situation with the effect of the measure. At a few points the bed level does not meet the criterion, but in general the bed level did not rise during the computation. In total 11.5 $m^3s^{-1}$ was removed to reach this goal. Over the whole period this corresponds with as 173 million $m^3$ sand. This is a very high amount. For reference: the yearly amount of maintenance in the Western Scheldt is 1 million $m^3$.

Table 12: Dredging locations and volume

| Distance from Xiaolangdi [m] | Dredge volume [$m^3s^{-1}$] |
|---|---|
| 115000 | 2 |
| 140000 | 2 |
| 148000 | 1 |
| 203000 | 1 |
| 257000 | 0.5 |
| 277000 | 2.5 |
| 287000 | 2.5 |

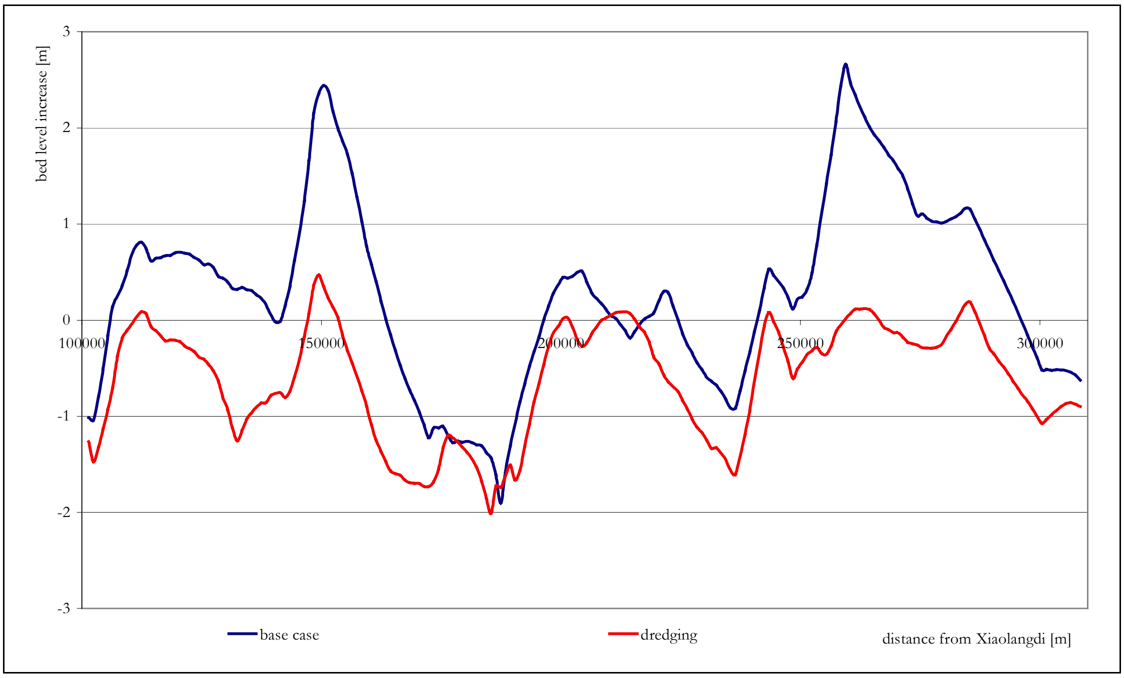


Figure 57: Difference in bed level increase due to the measure dredging

The influence of the measure on the water levels is positive, see Figure 58. Not only in he project area but also further up- and downstream. Throughout the reach the water levels drops. The maximum water level drop is about 37 cm and the average water level drop is about 20 cm over at least 200 km.

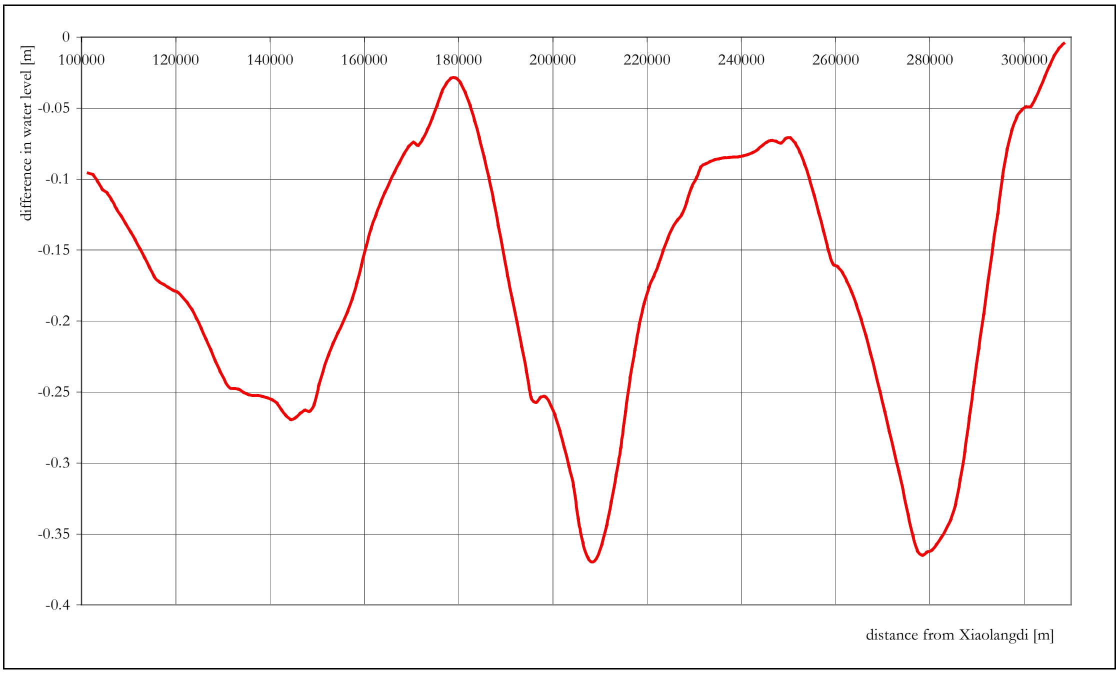


Figure 58: Influence of the measure dredging on the water level

### 4.4.5 FLOOD PLAIN LOWERING

The starting point of this measure is the removal of the unregistered dikes. The results of this measure are already described in section 4.4.2. The objective of this new measure is not only to remove these dikes, but also to dredge at specific locations in order to increase the storage area. Figure 59 shows four examples of the part of the area that was dredged. The same was done for all the cross-sections between Huayuankou and Jiahetan. Based on the cross-sections the average area that has to be removed is 1500 $m^3/m$. The total volume of sand that was removed is 158 million $m^3$. The flood plain lowering implies the evacuation of the people living on the flood plains during a flood or even better the resettlement of the people living on the flood plains. Between Huayuankou and Jiahetan 1.1 million people live on the flood plains.

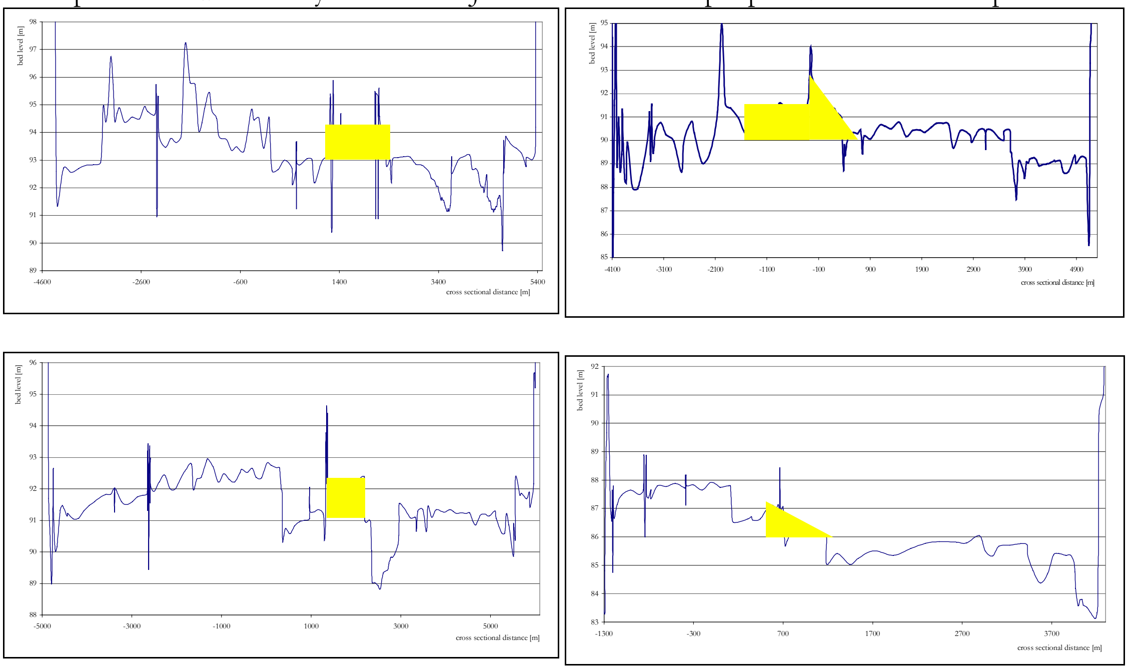

Figure 59: Example of dredging between the dikes

The results of the measure are plotted in Figure 60. The water level drops even more than the in the case of removal of unregistered dikes. This is important because the starting point of this measure is the removal of these dikes. The maximum water level drop is almost 60 cm and the average water level drop is about 30 cm for 150 km. This measure also influences the upstream and the downstream water levels. The downstream effects are negative. The reason for the downstream effect is the same as explained for the flood plain widening. The upstream effect is positive.

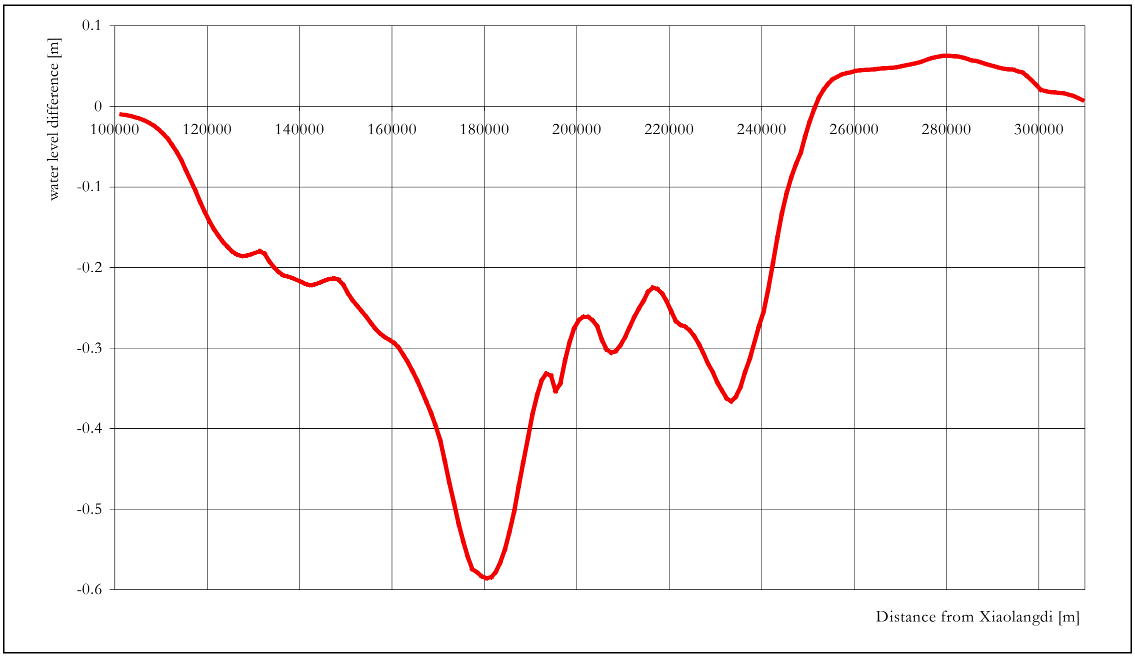


Figure 60: Influence of the measure flood plain lowering

### 4.4.6 CONCLUSIONS

All the measures improve the safety of the lower reach of the Yellow River to a certain extent. The effects are summarised in Table 13, via the average and the maximum water level drop. The distance where the average water level is found, is also plotted in this table.

Table 13: All the measures and their influence on the water level

| Measure | Maximum water level drop [m] | Average water level drop [m] | Distance [km] |
|---|---|---|---|
| Flood plain lowering | 0.42 | 0.2 | 120 |
| Detention | 0.2 | 0.1 | 70+ |
| Removal of unregistered dikes | 0.25 | 0.1 | 140 |
| Dredging | 0.37 | 0.2 | 200+ |
| Flood plain lowering | 0.58 | 0.3 | 150 |

There is a difference in effect between the measures, but all have in common that they lower the water level as compared with the base case. The quantitative results in the table are probably not very accurate, but they are qualitatively correct. The effects of the measures on the safety are only indicative. For example, the measure "detention" shows an average water level drop of 0.1 m. This is based on a topping discharge of 11000 $m^3s^{-1}$. If the discharge were topped at 9000$m^3s^{-1}$, as shown in Figure 56, the results would have been quantitatively different but qualitatively the same.

The upstream and downstream extents of the effects are almost the same for each measure, except for "detention". All measures investigated meet the objective of the study, which is improving the flood control in the lower reach. Therefore, all measures are marked as promising and are taken into account in the next phase, the selection phase. During this phase of the study, the combination of measures results in strategies that can improve the flood control.

# 5 STRATEGY DESIGN AND EVALUATION

The last phase of the framework is the selection phase, see also Figure 61. The purpose of this phase is to combine the promising measures into a limited number of promising strategies which, after detailed assessment of their effects, are presented in a scorecard.

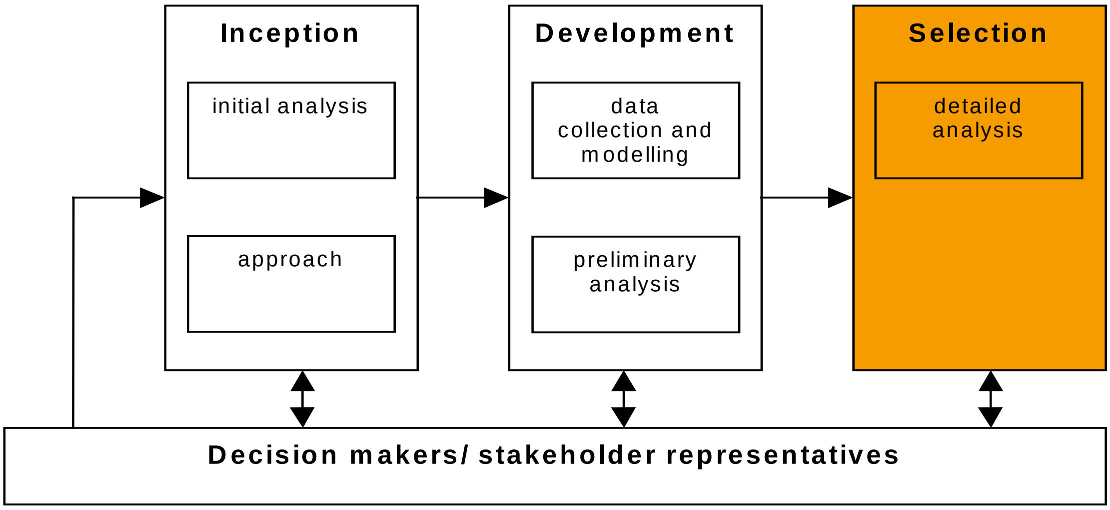


Figure 61: The selection phase of the analytical framework

Section 5.1 gives a detailed description of the criteria, both in a qualitative and quantitative way. Section 5.2 describes the formulation of the strategies. The assessment of the strategies is carried out in section 5.3.

## 5.1 CRITERIA

Criteria are units which express the extent that strategies are able to reach certain objectives. Hence, the formulation of the criteria should be based on the objective of this study, which is to improve flood control. The most important criterion belonging to this objective is safety. Furthermore the characteristics of the strategy implementation are also used as criteria. Characteristics of strategy implementation are costs, flexibility and realisation period. The criterion social impact is added because in most of the strategies many people are involved which live close to the Yellow River. The strategies may have a serious impact on their lives.

**Safety**

The criterion safety is mainly characterised by the water level and can be divided into two sub-criteria for this case.

The first sub-criterion is the drop in the water level in the section between Huayuankou and Jiahetan in comparison to the base situation. The indicator for these sub-criteria is the average water difference in the section Huayuankou and Jiahetan.

The second sub-criterion is the effect of the strategy on the water level up- and downstream. This criterion will only be described in a qualitative way and is rewarded with a positive or negative score, not with values.

**Costs**

The criterion costs is defined as monetary value. The economic costs can be defined as being all expenses incurred when executing a strategy, which is the sum of the following factors:

1. Construction costs
2. Loss of land
3. Maintenance costs
4. Other costs

In the scope of this study only the first two components are taken into account because these are expected to form the biggest amount in the total costs. A rough estimate of the cost of each strategy has been calculated from unit costs such as dredging one cubic meter of sediment, relocation of one inhabitant and construction of one kilometre dike of 10 metres high. The calculation of the costs is carried out for a 15 years period because some strategies have high one-time investments whereas other strategies have high annual costs. The assumed discount rate for the calculation of the costs for each of the strategies is 10%. All the unit costs are summarised in Table 14 including the dimensions. The calculated costs for each of the strategies are based on the unit costs as described in Table 14. The results do not give the exact costs but can be seen as a good estimation of the real costs. This estimation enables the comparison of the costs of the strategies.

Table 14: Unit costs

| | **Unit costs** | **Dimension** |
|---|---|---|
| Resettlement | 43000 | RMB/person |
| Dike construction | 20 | RMB/$m^3$ |
| Dredging | 5.7 | RMB/$m^3$ |
| Land acquisition | 2500 | RMB/10000 $m^2$ |
| Flood plain lowering | 8550 | RMB/$m^3$ per m |
| Construct new dike | 8000 | RMB/$m^3$ per m |
| Removal unregistered dikes | 45 | RMB/$m^3$ per m |

Some of the unit costs were provided by the YRCC, whereas others were calculated with the help of other unit costs. The detailed description of the formulation of the unit costs is given below.

- The real costs for resettlement are unknown and difficult to specify. To get an impression of the resettlement cost, the costs of the resettlement for the Xiaolangdi project are used. The total costs for resettlement for the Xiaolangdi project are 8.6 billion RMB for 197000 people. This is the same as 43000 RMB per person. This number is used as unit cost for this project to be able to give an indication of the resettlement costs.
- The costs for dike construction consist of labour and soil. The number obtained from the YRCC is 20 RMB/$m^3$ for dike construction. These costs include labour and machinery.
- The costs for dredging are obtained from the YRCC. These costs are 5.7 RMB/$m^3$, which include labour and machinery.
- The costs for land acquisition are on average 2500 RMB per 10000 $m^2$. The real costs for land vary between 2000 RMB and 3500 RMB.
- A rough estimation for the flood plain lowering is 1500 $m^3$ per m. This estimation is based on the area that has to be dredged as shown in Figure 59. The costs for dredging are 5.7 RMB/$m^3$. The unit costs for one meter of flood plain lowering equals 8550 RMB.
- The set back of dikes implies constructing a new dike. The height of the dikes is 10m and the width on the top is also 10 m, the slope is 1:3. The total dike volume is 400$m^3$ per m.

The costs for dike construction agree with 20 RMB/$m^3$. The unit costs for one meter dike construction equals 8000 RMB.

- The costs of the removal of the dikes are comparable with the costs of flood plain lowering. The surface area of these dikes is estimated on 8 $m^3$ per m. The costs for dredging equal 5.7 RMB/$m^3$. The total costs for the removal of the dikes are 45 RMB/$m^3$ per meter.

**Flexibility**

The flexibility is determined by the extent that the strategy can be adapted if that will be needed in future. Due to a number of scenarios, like climate change or increase or decrease of population, other strategies can become more interesting. If a strategy asks for high investments or many changes in the current river system it is more difficult to change to another strategy. The qualification flexible or not is described in a qualitative way and presented with the use of the relative values (see Table 23).

**Realisation period**

The realisation period is mainly a time factor that is determined by the complexity of the strategy and the techniques needed to implement the strategy. The flood control must be improved on a short-term. Strategies that ask for a long implementation period are less favourable than strategies with a short realisation period. The description of the realisation period is carried out in a qualitative way and presented with the use of the relative values (see Table 23). If possible the expected realisation period was estimated.

**Social impact**

The social impact is the impact of the strategy on the people living in the affected area. It is not only the extent of the impact but also the number of people that face the impact. If a strategy has a great impact it indicates that many people are involved. The number of people involved in a strategy, and in most cases the number of people that have to be resettled, are presented in the scorecard.

## 5.2 STRATEGIES

All preliminary measures seemed promising and can be used as ingredients for the formulation of strategies in terms of flood risk lowering. The measure detention is defined as an extra strategy and not used in the formulation of the strategies, because this measure is only used in emergency cases. This strategy is called “Emergency”. The remaining four measures can be combined to many different strategies. To structure all these combinations the following themes have been defined:

- Minimum costs;
- Maximum preservation.
- Maximum flood control;

Based on these themes the different measures are combined in such a way that they fulfil the themes as good as possible. It implies that three strategies are formed. In addition to these 3 strategies a fourth was defined as the strategy “Emergency”. The combination of measures taken into account in these strategies is described in the sub-sections.

### 5.2.1 STRATEGY: MINIMUM COSTS

The objective of this strategy it to improve the flood control as good as possible with minimum costs. A number of combinations of measures were formulated to figure out which combination satisfies was the best. A combination of the measure flood plain widening and continuous dredging is relatively cheap and also has a positive impact on the water levels. The assessment of the strategy is carried out for the different criteria.

#### Safety

The safety will improve due to the implementation of this strategy. The water level drop is on average 31 cm between Huayuankou and Jiahetan, see also Figure 62. The maximum water level drop is 48 cm. The strategy has a positive effect on both the up- and downstream water level, but mainly on the upstream water level. The influence is visible up to 60 km upstream of the implementation of the strategy.

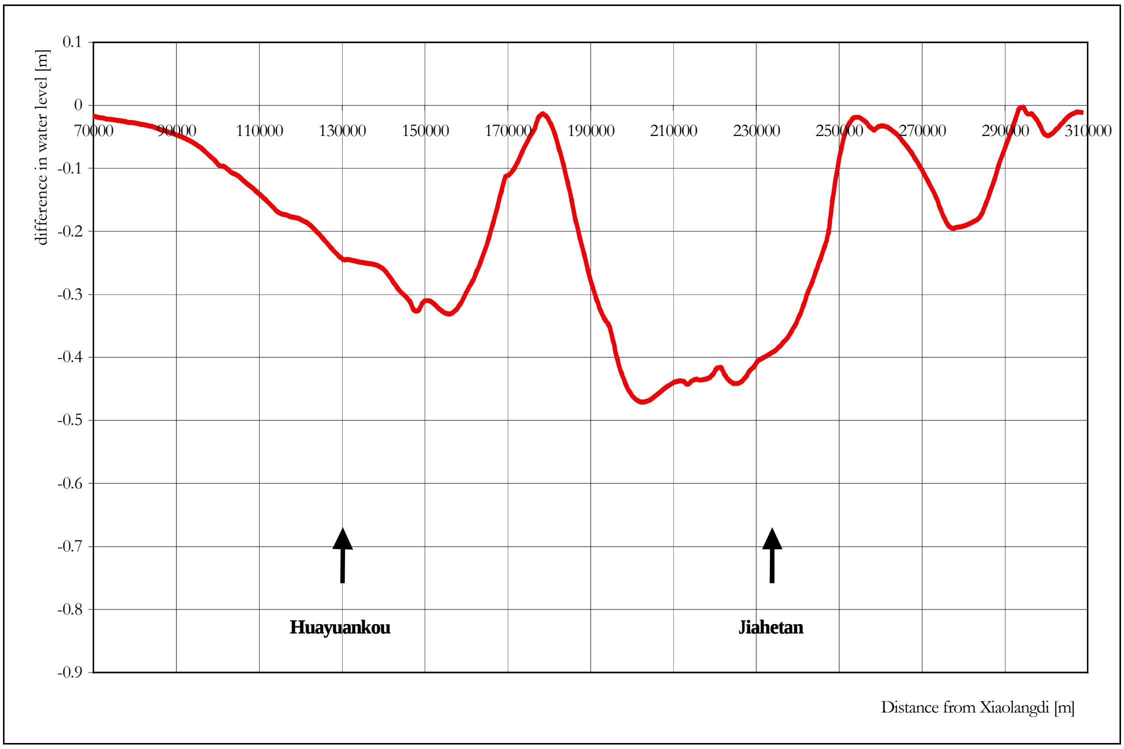


Figure 62: Water level drop for strategy "Minimum costs"

#### Costs

The costs of the strategy "Minimum costs" consist of two components; the costs for the flood plain widening and costs for the continuous dredging. The costs for flood plain widening consist of the construction of a new dike on both sides, the acquisition of the land and the relocation of the people living on this land. The calculation of the total costs is based on a fifteen years period, because the implementation of the different parts of the strategy will take more than one year and will sometimes return every year. Table 15 gives an impression of a possible implementation schedule of this strategy. The action dredging will return annually, whereas the flood plain widening and the resettlement are expected to take five years. The land acquisition is expected to take two years. The percentage of implementation in a certain year is expected to be high in the first year and is decreasing the next years. The costs are calculated with the help of the unit costs and the numbers presented for the measures in section 4.4. The period is the year of implementation of each of the actions.

Table 15: Possible implementation- and time schedule for strategy "Minimum costs"

| Occurrence | Action | Percentage of implementation | Costs (million RMB) | Period | Term |
|---|---|---|---|---|---|
| A | Dredging | 1 | 980 | 1 - 15 | 15 |
| B | Flood plain widening | 0.3 | 408 | 3 | 1 |
| C | Flood plain widening | 0.25 | 340 | 4 | 1 |
| D | Flood plain widening | 0.2 | 272 | 5 | 1 |
| E | Flood plain widening | 0.15 | 204 | 6 | 1 |
| F | Flood plain widening | 0.1 | 136 | 7 | 1 |
| G | Resettlement | 0.3 | 3870 | 1 | 1 |
| H | Resettlement | 0.25 | 3225 | 2 | 1 |
| I | Resettlement | 0.2 | 2580 | 3 | 1 |
| J | Resettlement | 0.15 | 1935 | 4 | 1 |
| K | Resettlement | 0.1 | 1290 | 5 | 1 |
| L | Land acquisition | 0.5 | 100 | 1 | 1 |
| M | Land acquisition | 0.5 | 342 | 2 | 1 |

Table 16 shows the occurrence of the actions in each of the years and the related costs for each of the years and the total costs. The total costs are 13 billion RMB.

Table 16: Total NPV costs for the strategy "Minimum costs"

| Period | Occurrence | Costs (million RMB) | Costs including discount (million RMB) |
|---|---|---|---|
| 1 | A, G, L | -4,950 | -4,950 |
| 2 | A, H, M | -980 | -810 |
| 3 | A, B, I | -1,388 | -1,043 |
| 4 | A, C, J | -980 | -669 |
| 5 | A, D, K | -2,542 | -1,578 |
| 6 | A, E | -1,184 | -668 |
| 7 | A, F | -1,116 | -572 |
| 8 | A | -980 | -457 |
| 9 | A | -980 | -415 |
| 10 | A | -980 | -377 |
| 11 | A | -980 | -343 |
| 12 | A | -980 | -312 |
| 13 | A | -980 | -283 |
| 14 | A | -980 | -258 |
| 15 | A | -980 | -234 |
| **Total NPV costs (million RMB):** | | | **-12,977** |

**Flexibility**

A part of the strategy consists of flood plain widening. The flood plain widening has high one-time investments. A new dike has to be built and all the people have to relocate before the flood plain widening can be used. The continuous dredging is flexible because it can start or end any time. In total the strategy "Minimum costs" is not very flexible mainly due to the flood plain widening.

## Realisation period

The realisation period of the dredging is short, actually it can start at once. The realisation period of the flood plain widening is also relatively short. The new dike can be constructed and afterwards the old dike can be removed. In the mean time the people can be relocated. In total the realisation period for this strategy is short.

## Social impact

The social impact is relatively low. The number of people that have to resettle is expected to be 300000, but the amount of people is based on estimation and therefore it may be 20% higher than the estimated number of people.

### 5.2.2 STRATEGY: MAXIMUM PRESERVATION

The strategy "Maximum preservation" is based on a minimum change of the current setting. The strategy consists of flood plain lowering and dredging because both measures can be adopted in the current setting. The assessment of the strategy is carried out for each of the different criteria.

## Safety

The strategy "Maximum preservation" improves the safety. The average water level drop is 41 cm and the maximum water level drop is 62 cm, see also Figure 63. Both the up- and downstream influence the water level positively, the water level drops up- and downstream. The influence is visible for at least 60 km upstream of the implementation of the strategy.

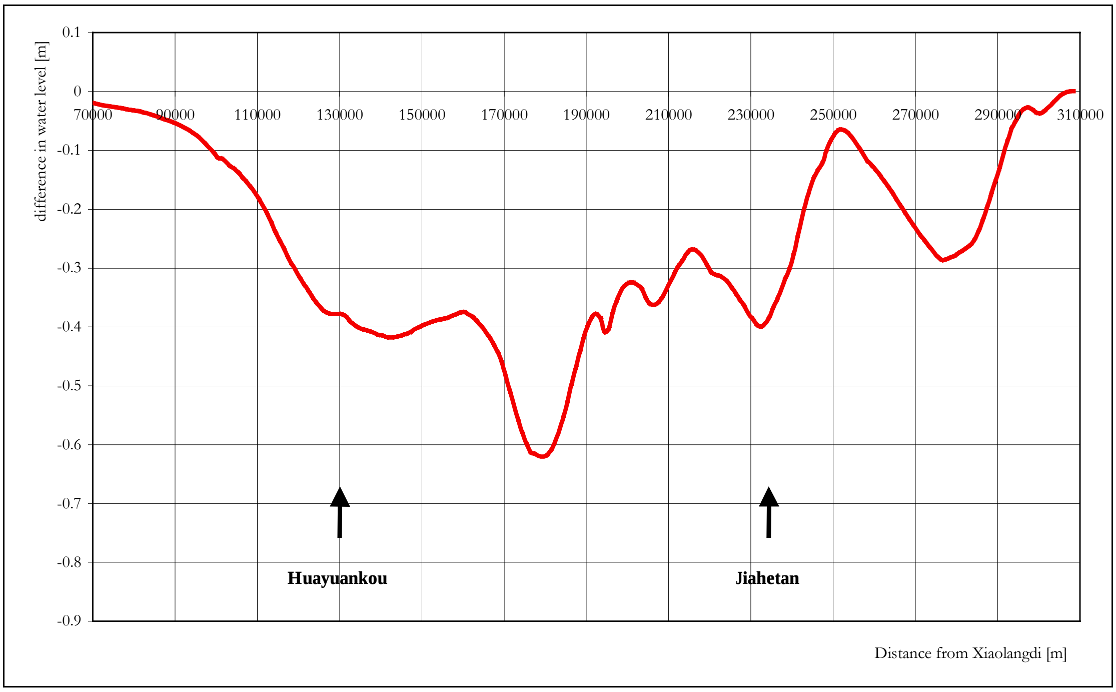


Figure 63: Water level drop for strategy "Maximum preservation"

## Costs

The total costs for this strategy consists of the costs for flood plain lowering and the costs for dredging. The costs for flood plain lowering consist of the removal of the sediment and the relocation of the people. For this strategy 75% of the people living on the flood plains will be resettled. Table 17 gives an impression of a possible implementation schedule including the actions and the year of implementation. This schedule is used to calculate the total costs for this strategy.

Table 17: Possible implementation- and time schedule for strategy "Maximum preservation"

| Occurrence | Action | Percentage | Costs (million RMB) | Period | Term |
|---|---|---|---|---|---|
| A | Dredging | 1 | 980 | 1 - 15 | 15 |
| B | Resettlement | 0.3 | 10320 | 1 | 1 |
| C | Resettlement | 0.25 | 8600 | 2 | 1 |
| D | Resettlement | 0.2 | 6880 | 3 | 1 |
| E | Resettlement | 0.15 | 5160 | 4 | 1 |
| F | Resettlement | 0.1 | 3440 | 5 | 1 |
| G | Flood plain lowering | 0.5 | 449 | 6 | 1 |
| H | Flood plain lowering | 0.5 | 449 | 7 | 1 |

The total NPV costs and the calculation of these costs is shown in Table 18. The costs for dredging return every year, whereas the costs for resettlement only return the first five years. For the calculation of the NPV costs a discount rate of 10% was used as for each of the strategies. The total NPV costs are about 37 billion RMB.

Table 18: Total NPV costs for the strategy "Maximum preservation"

| Period | Occurrence | Costs (million RMB) | Costs including discount (million RMB) |
|---|---|---|---|
| 1 | A, B | -11,300 | -11,300 |
| 2 | A, C | -9,580 | -7,917 |
| 3 | A, D | -7,860 | -5,905 |
| 4 | A, E | -6,140 | -4,193 |
| 5 | A, F | -4,420 | -2,744 |
| 6 | A, G | -1,429 | -806 |
| 7 | A, H | -1,429 | -733 |
| 8 | A | -980 | -457 |
| 9 | A | -980 | -415 |
| 10 | A | -980 | -377 |
| 11 | A | -980 | -343 |
| 12 | A | -980 | -312 |
| 13 | A | -980 | -283 |
| 14 | A | -980 | -258 |
| 15 | A | -980 | -234 |
| **Total NPV costs (million RMB):** | | | **36,286** |

**Flexibility**

The flexibility of this strategy is comparably good. The removal of the sediment and the dredging have a low investment, only the resettlement of the people asks for a high investment. Moreover the implementation of the strategy it is always useful to relocate the people living on the floodplains because on the floodplains the risks of casualties or damage are very high.

### Realisation period

The realisation period for the dredging is short as it can start immediately. The realisation period for the flood plain lowering is relatively long. The removal of the sediment is not a problem but the resettlement of the people will take at least five years. The total realisation period for the strategy “Maximum preservation” is at least five years.

### Social impact

The social impact is relatively high, although the social impact is even higher for two other strategies. The relocation of 800000 people have taken into account but it should even have been better to relocate all the people living on the flood plains, which are 1.1 million people.

## 5.2.3 STRATEGY: MAXIMUM FLOOD CONTROL

The objective of the strategy “Maximum flood control” is the same as the objective of this study; to improve the flood control as much as possible. This strategy consists of a combination of the measures flood plain lowering, dredging flood plain widening. This combination gave the best results in terms of safety. The screening of the strategy is carried out for the different criteria.

### Safety

The safety was improved due to the strategy. The average water level drop is 48 cm and the maximum water level drop is 82 cm, see also Figure 64. The up- and downstream are both positive and even better than the positive up- and downstream effects of the other strategies.

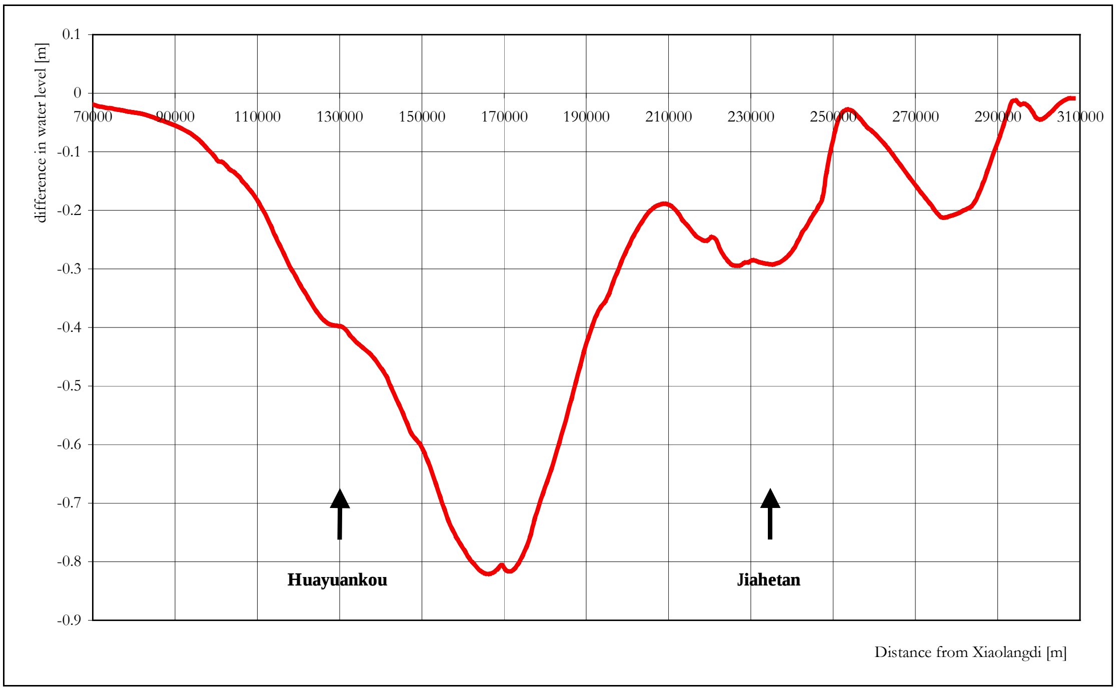


Figure 64: Water level drop for strategy “Maximum flood control”

### Costs

The costs for the strategy “Maximum flood control” consist of the costs for dredging, the costs for flood plain lowering and the costs for flood plain widening. The costs for flood lowering and flood plain widening both consist of resettlement. In total 1.1 million have to resettle. Besides the costs for resettlement, the costs for flood plain lowering also consist of the removal of the sediment and the costs for flood plain lowering also consist of the costs for land acquisition and the construction of new dikes. Table 19 gives a possible implementation schedule for this strategy including costs and year of implementation for each of the actions.

Table 19: Possible implementation- and time schedule for strategy "Maximum flood control"

| Occurrence | Action | Percentage | Costs (million RMB) | Period | Term |
|---|---|---|---|---|---|
| A | Dredging | 1 | 980 | 1 - 15 | 15 |
| B | Resettlement | 0.3 | 14190 | 2 | 1 |
| C | Resettlement | 0.25 | 11825 | 3 | 1 |
| D | Resettlement | 0.2 | 9460 | 4 | 1 |
| E | Resettlement | 0.15 | 7095 | 5 | 1 |
| F | Resettlement | 0.1 | 4730 | 6 | 1 |
| G | Flood plain lowering | 0.5 | 448 | 6 | 1 |
| H | Flood plain lowering | 0.5 | 448 | 7 | 1 |
| I | Flood plain widening | 0.3 | 269 | 3 | 1 |
| J | Flood plain widening | 0.25 | 224 | 4 | 1 |
| K | Flood plain widening | 0.2 | 179 | 5 | 1 |
| L | Flood plain widening | 0.15 | 134 | 6 | 1 |
| M | Flood plain widening | 0.1 | 89 | 7 | 1 |
| N | Land acquisition | 0.5 | 100 | 1 | 1 |
| O | Land acquisition | 0.5 | 100 | 2 | 1 |

The total NPV costs and the calculation of the total costs including the discount rate is shown in Table 20. There are a lot of activities in the first years and consist of the main part of the total costs. Another implementation schedule would give different NPV costs. The total costs for the strategy "Maximum flood control" are43 billion RMB.

Table 20: Total NPV costs for the strategy "Maximum flood control"

| Period | Occurrence | Costs (million RMB) | Costs including discount (million RMB) |
|---|---|---|---|
| 1 | A, N | -1,080 | -1,080 |
| 2 | A, B, O | -15,270 | -12,620 |
| 3 | A, C, I | -13,074 | -9,823 |
| 4 | A, D, J | -10,664 | -7,284 |
| 5 | A, E, K | -8,254 | -5,125 |
| 6 | A, F, G, L | -6,293 | -3,552 |
| 7 | A, H, M | -1,519 | -779 |
| 8 | A | -980 | -457 |
| 9 | A | -980 | -415 |
| 10 | A | -980 | -377 |
| 11 | A | -980 | -343 |
| 12 | A | -980 | -312 |
| 13 | A | -980 | -283 |
| 14 | A | -980 | -258 |
| 15 | A | -980 | -234 |
| **Total NPV costs (million RMB):** | | | **42,949** |

**Flexibility**

The strategy “Maximum flood control” is not flexible. The resettlement of more than one million people will take a lot of time. Moreover a lot of different aspects have to be carried out for the total realisation of the strategy.

**Realisation period**

The realisation period is relatively long. A lot of different aspects have to be implemented and the number of people that need to resettle is very high. The expected implementation period is more than 10 years and maybe even longer.

**Social impact**

The social impact is high. The number of people that have to resettle is more than one million, which is the highest of all the strategies. It would even be better to resettle all the people that live on the flood plains.

### 5.2.4 STRATEGY: EMERGENCY

The strategy “Emergency” is an extra strategy with special circumstances. It is not a regular strategy but a strategy that is only active in emergency cases. Moreover the physical implementation of this measure is already realised to a certain extent. Beijindi is the first detention area in the lower reach and the most important one because detention areas have a downstream effect on the water level. However inside the Beijindi detention the population density is 650 people per $km^2$ and the total population is 1.5 million people. Ideally designated flood areas should meet the criteria of low population density and fixed assets. In case these criteria are not met, the use of the detention areas might result in considerable damages and a high number of casualties within the detention area. Second the prospect of these damages and casualties might well mean that the detention area will not be allowed to flood timely. If this is the case, the only effect of a detention area is to create a false sense of security, resulting in insufficient flood management measures elsewhere.

Based on the criteria for designated flood areas Beijindi detention area is not suitable to actually reduce flood risk in the lower reach of the Yellow River. This implies that a lot of measures have to take place to make Beijindi a suitable detention area. The evaluation with the criteria safety, costs, flexibility and realisation period is based on that fact. Moreover most historical dike breaches took place before Beijindi was assigned as detention area. Figure 19 shows that the flood prone areas at both banks mainly exist due to dike breaches between Huayuankou and the first detention area, Beijindi. Therefore it is interesting to build another detention area or to enlarge the Beijindi detention area up to Huayuankou. In this strategy the inlet of Beijindi detention basin is shifted to Huayuankou. The flood peak is topped at a discharge of $10000 m^3 s^{-1}$.

**Safety**

The safety is improved but only in the section downstream of the inlet of the detention area, which is at Huayuankou. The average water level drop is 0.41 m and the maximum water level drop is 55 cm, see also Figure 65. The water level drop depends on the amount of water that was discharged in the detention basin. Upstream of the detention area the safety is not improved. Downstream of the detention area the safety is improved and not only within the project area but it is expected to improve the flood control in the whole lower reach downstream of the inlet of the detention basin.

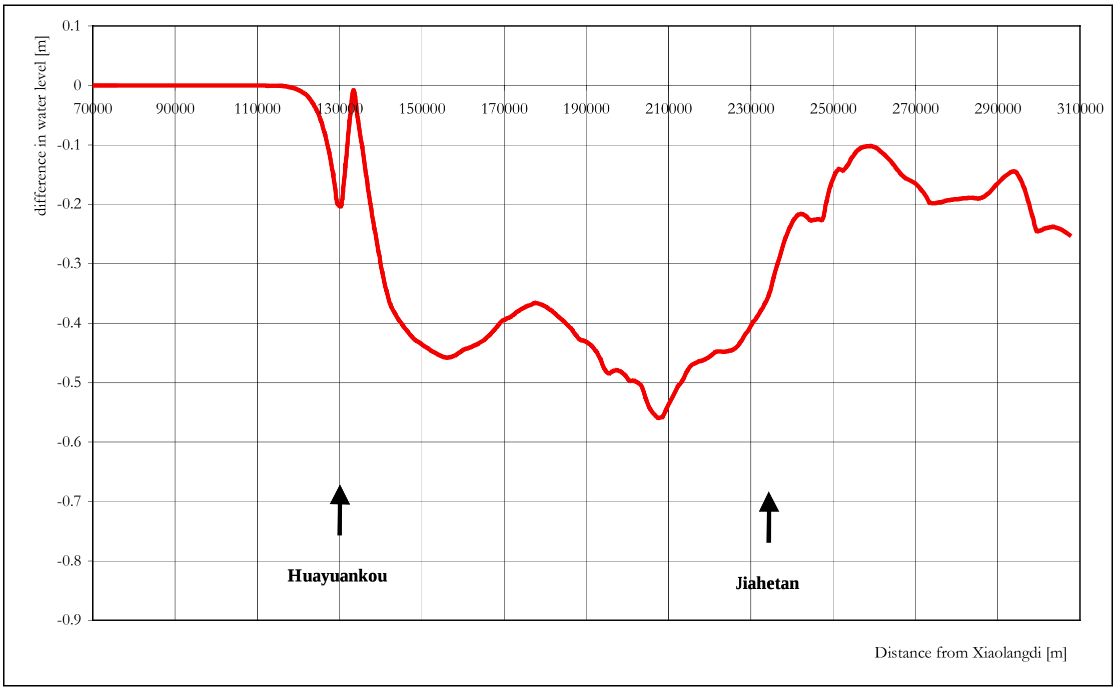


Figure 65: Water level drop for strategy "Emergency"

### Costs

The physical environment is already there. Dikes, inlets and outlets are already constructed. The costs for this strategy are the resettlement of most of the people living in the detention basin. At the moment 1.5 million people live in the detention area and at least 1 million have to resettle. The costs for land are included in the resettlement cost and therefore don't have to be taken into account anymore. The costs for the extension of the detention basin are not taken into account. Table 21 shows a possible implementation schedule for this strategy. In this schedule the resettlement is estimated to last five years.

Table 21: Possible implementation- and time schedule for strategy "Emergency"

| Occurrence | Action | Percentage | Costs (million RMB) | Period | Term |
|---|---|---|---|---|---|
| A | Resettlement | 0.3 | 12900 | 1 | 1 |
| B | Resettlement | 0.25 | 10750 | 2 | 1 |
| C | Resettlement | 0.2 | 8600 | 3 | 1 |
| D | Resettlement | 0.15 | 6450 | 4 | 1 |
| E | Resettlement | 0.1 | 4300 | 5 | 1 |

Table 22 shows the calculation of the total NPV costs for the strategy "Emergency". Based on the occurrence of the actions the total costs are calculated. The implementation is estimated only to last five years. An other implementation schedule would give different NPV costs. The total NPV costs are about 35 billion RMB.

Table 22: Total NPV costs for the strategy "Emergency"

| Period | Occurrence | Costs (million RMB) | Costs including discount (million RMB) |
|---|---|---|---|
| 1 | A | -12,900 | -12,900 |
| 2 | B | -10,750 | -8,884 |
| 3 | C | -8,600 | -6,461 |
| 4 | D | -6,450 | -4,405 |
| 5 | E | -4,300 | -2,669 |
| 6 | | 0 | 0 |
| 7 | | 0 | 0 |
| 8 | | 0 | 0 |
| 9 | | 0 | 0 |
| 10 | | 0 | 0 |
| 11 | | 0 | 0 |
| 12 | | 0 | 0 |
| 13 | | 0 | 0 |
| 14 | | 0 | 0 |
| 15 | | 0 | 0 |
| **Total NPV costs (million RMB):** | | | **-35,321** |

**Flexibility**

The implementation of this strategy asks for a high investment and moreover the physical environment is already constructed. So the flexibility is low. On the other hand it is rather difficult to change the policy for this area. The land can also be used for living without change in the physical environment. In that sense this strategy is flexible.

**Realisation period**

The realisation period is relatively long. Although the dikes and inlets are already constructed, the people inside the detention have to resettle. The resettlement of one million people is expected to take at least five years and maybe even longer.

**Social impact**

The social impact is relatively high. For this strategy it was recommend to relocate at least one million people but it is even better to relocate all the people living in Beijindi detention basin.

## 5.3 IMPACT ASSESSMENT

The impact assessment and evaluation of the strategies consists of the comparison of the four strategies. The comparison is based on the criteria safety, costs, flexibility and realisation period. The score on screening of the criteria is only qualitative and visualised with a relative value to indicate of the strong and weak points of a strategy. The relative value for the results is divided in five groups, see Table 23. Very good indicates that the strategy fulfils the criteria completely. Very bad indicates that the strategy does not fulfil the criteria at all.

Table 23: Indicators for the qualitative results

| Indicator | Relative value |
|---|---|
| Very good | ++ |
| Good | + |
| Reasonable | +/- |
| Bad | - |
| Very bad | - - |

The results are plotted in a table in order to make it easier to compare the strategies. In this case a scorecard is used, see also Table 24. The columns of the scorecard represent the different strategies as described in section 5.2. The rows represent the impact of the strategies with respect to the given criteria, see also section 5.1.

Table 24: Scorecard for the strategies

| Criteria \ Strategy | | Minimum costs | Maximum preservation | Maximum flood control | Emergency |
|---|---|---|---|---|---|
| Safety | Difference | 0.31 | 0.41 | 0.48 | 0.41 |
| | Up-down stream | + | + | + | + |
| Costs [$10^9$ RMB] | | 13 | 37 | 43 | 35 |
| Flexibility | | - | ++ | - | +/- |
| Realisation | | + | - | - - | - |
| Social impact | | 300000 | 800000 | 1100000 | 1000000 |
| | | | | | |
| Rankings: | | Best | Middle | Worst | |

All the strategies fulfil the first and the most important criterion, the safety, which is also the objective of this study. In all cases the flood control is improved compared with the base case situation, although the extent of satisfying the criterion differs between the strategies. The sub-criteria "effect up-and downstream" was equal rewarded for all strategies because for each strategy there was a positive up- or downstream effect and therefore did not influence the criterion safety.

The costs for all strategies are high. The main reason is the costs for the resettlement of the people living on the flood plains or the people living in Beijindi detention basin. Without taking into account these costs, the total costs would be much less. Moreover the people living on the flood plains are not allowed to live there, which might imply that the government is not willing to pay the resettlement for these people.

The criterion flexibility is only satisfied for the strategy "Maximum preservation". The other strategies have high investment costs, mainly due to the resettlement of the people and due to this these strategies are less flexible.

Also for the last two criteria the restriction seems to be the resettlement of the people. The social impact is very high because so many people have to move, which creates a lot of uncertainty among these people. The realisation period is also relatively long for the strategies that include resettlement. To relocate so many people takes a lot of time.

Overall, it can be said that the different strategies create a lot of possibilities to improve the flood control for the Yellow River between Xiaolangdi and Gaocun. Even outside the project area the flood control is improved. Moreover the bottleneck for the implementation of the strategies seems to be the resettlement of the people. For almost each criterion the resettlement seemed to be the bottleneck.

It is stressed that above scorecard has only an indicative value (also see section 1.2 and 4.4.6). The main aim of this study was to illustrate, the approach and, the measures as followed in the Netherlands policy "Room for the River". Data and time constraints prevented to carry out a detailed analysis.

# 6 CONCLUSIONS AND RECOMMENDATIONS

## 6.1 CONCLUSIONS

The design flood discharge in the lower reach of the Yellow River is relatively low. However the probability of flood increases because of the decreasing flood conveyance capacity and the effects of the decreasing annual inflow. Moreover in case of a flood, the increasing population and the economic development causes much more economical and social damage than ten years ago. When looked at the measures taken in order to control the river in the last fifty years, the approach focuses on flood prevention by raising and strengthening the embankments, and by the construction of dams like the Sanmenxia dam and more recently the Xiaolangdi dam. However, it seems that these traditional types of measures will not be able to create a sustainable and safe water resources system for the lower reach of the Yellow River.

The objective of this project is to study the flooding problems in the lower reach of the Yellow River and investigate how far the approach and measures as applied in the Dutch "Room for the River" policy can help in improving the flood control for the Yellow River between Xiaolangdi and Gaocun. The complexity of the morphology, the uncertainties in the modelling and the limited data available of this water resources system made it impossible to set up a detailed study including quantitative results with a relatively small range of uncertainty. However it was possible to conclude that the "Room for the River" policy can be of use to the lower reach of the Yellow River. The measures put forward in this policy, like widening and deepening the river, are adapted to the study area and screened with a 1D-morphodynamic model. All these measures seemed to be able to improve the safety of the lower reach of the Yellow River to a certain extent.

In the last phase of the study these measures were combined into four strategies. All the strategies fulfil the most important criterion of this study, to improve the safety of the lower reach of the Yellow River. The different strategies show that there are a lot of possibilities to improve the flood control between Xiaolangdi and Gaocun. The screening of the impact of the four strategies put forward some interesting results. The bottleneck for the implementation of the strategies is the number of people living on the flood plains and in the Beijindi detention basin. For each of the strategies at least 300000 people have to resettle or evacuate, but in most cases the number is even beyond one million. This is also the most important reason that the implementation of these strategies is very costly. At least 60% of the estimated costs are related to the resettlement of the inhabitants.

## 6.2 RECOMMENDATIONS

The data for the study was obtained from the YRCC in China. It was difficult to obtain enough data whereas most of the required data seemed to be available. It is recommended to continue the co-operation with the universities and institutes in China in order to further improve the relations. During the discussions between China and the Netherlands attention has to be paid to the mutual benefits of working together and using each other strong points. The data collection may be part of this discussion because without sufficient and reliable data it is impossible to carry out a research project.

The modelling of the Yellow River had a number of uncertainties. Due to the limited number of cross-sections, the unregistered dikes in the cross-sections, the limited number of calibration points and the complexity of the morphology, the computation of the water levels was difficult and is to a certain extent uncertain. First of all it is recommended to improve and to extend the data collection. Second it is recommended to investigate the morphological processes more in detail, especially in combination with the numerical modelling. It is recommended to do this co-operatively in order to bring together the knowledge of China and the Netherlands.

The Dutch “Room for the River” policy seems very useful and promising for the lower reach of the Yellow River. It may be able to bring flood control to a much safer and more sustainable situation. Therefore it is recommended to continue this research in order to determine the benefits more in detail. If possible it is recommended to set up a 2D-numerical model to create a better insight in the obstacles, like the unregistered dikes, in the flood plains and their influence on the water motion.

The formulated strategies are promising in terms of safety but on the other hand the implementation of the strategies seems very costly and has a serious social impact. It is recommended to set up a flood damage study in order to figure out the benefits and not only the costs. This may show that the costs are relatively low.

The bottleneck for the improvement of the flood control seems to be the enormous number of people living on the flood plains and in the detention basins. It is recommended to do research in the situation of these people, for example their status and the reason why they live on the flood plains. On a higher level the existence and the quality of the early flood warning system and the evacuation plans has to be investigated.

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### Web-sites


(1) A comprehensive information base on today's China: http://www.chinatoday.com

(2) General Information of the People's Republic of China: http://www.chinatoday.com/general/a.htm#POPU

(3) Yellow River: Geographic and Historical Settings: http://www.cis.umassd.edu/~gleung/geofo/geogren.html

(4) http://www.environment.gov.au/epg/eianet/case_studies/cs_12.html

(5) http://www.angelfire.com/on/predictions/china.html