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Environmental flows assessment for the Lower Yellow River

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Introduction to this book

This book is a product of the River Health and Environmental Flow in China Project, a project undertaken between 2009 and 2012 by the International WaterCentre together with the Chinese Ministry of Water Resources and Ministry of Environmental Protection. The project formed part of the Australia-China Environment Development Partnership, a five-year program of work between the Australian and Chinese governments, funded by AusAID.

The River Health and Environmental Flow in China Project involved studies in the Yellow River, Liao River and Pearl River basins. This book is one of a number of publications that have been produced which document this work.

This book combines two reports on the Yellow River. Together, these reports describe the process of identifying environmental flow requirements for the lower Yellow River (the reach from Xiaolangdi Reservoir, the last major reservoir on the trunk stream, to the estuary).

The first report – Sites, Assets, Issues and Objectives – describes the method for assessing environmental flows that was used in the study. The report documents existing information on environmental assets in the lower Yellow River, divides the river into reaches, and identifies a series of key ecological assets that are the focus on the study. The assets are primarily a number of wetlands and the delta. For each of those assets, environmental flow objectives were determined, based on the requirements of different species (e.g. fish, birds) and physical processes (e.g. geomorphology) at each key site.

The second report – Ecohydraulic Modeling and Flow Recommendations – builds on the results of the first report. It describes a modeling process that was used to convert flow recommendations based on hydraulic criteria (i.e. depth of flow) into hydrologic criteria (i.e. a rate of flow). The report consolidates the multiple flow objectives into a set of flow recommendations for each reach of the river.

Acronyms

ACEDP	Australia–China Environment Development Partnership
ARI	Average Recurrence Interval
AusAID	Australian Agency for International Development
BBM	Building Block Methodology
BF	Bankfull-flow score
BI	Baseflow Index
BLRs	Blood Lipid Regulators
BOD_5	Biochemical Oxygen Demand
CITES	Convention on the International Trade in Endangered Species CITES
COD	Chemical Oxygen Demand
CSDPC	China State Development and Planning Commission
CTF	Cease to flow score
DEHP	Di (2-Ethylhexyl) Phthalate
DIN	Dissolved Inorganic Nitrogen
DO	Dissolved Oxygen
DTM	Digital Terrain Model
DWAF	South African Department of Water, Agriculture and Forestry
EN	Endangered
ENSM	Ecological Niche Suitability Model
EPA	Environmental Protetion Agency
GC	Gaocun
HF	High-flow score
HFF	High-flow rate of fall score
HFP	High-flow pulse score
HFR	High-flow rate of rise score
HYK	Huayuankou
IBA	Important Bird Areas
IFH	Index of Flow Health
IFIM	In-stream Flow Incremental Methodology
LF	Low-flow score
LFF	Low-flow rate of fall score
LFP	Low-flow pulse score
LFR	Low-flow rate of rise score
LJ	Lijin
LK	Luokou
MAF	Mean Annual Flow
MoA	Ministry of Agriculture
NFP	National Forest Protection
NSAIDs	Non-Steroidal Anti-inflammatory Drugs
OCO	Oxygen Consuming Organics
OCP	Organochlorine Pesticides
O/E	Observed/expected
PAE	Phthalic Acid Esters
PAH	Polycyclic Aromatic Hydrocarbons
PDO	Pacific Decadal Oscillation
SDR	Sediment Delivery Ratio
SK	Sunkou
SRP	Soluble Reactive Phosphorus
TN	Total Nitrogen
TP	Total Phosphorous
TSS	Total Suspended Solids
WSDR	Water Sediment Discharge Regulation
XLD	Xiaolangdi
YRCC	Yellow River Conservancy Commission
VU	Vulnerable

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Site, Assets, Issues and Objectives

Executive Summary

This report documents the scientific foundation for a set of environmental flow recommendations for the lower Yellow River. The primary readership for this report*, Environmental Flows Assessment for the Lower Yellow River: Site, Assets, Issues and Objectives* (this report) is the Scientific Panel charged with the task of setting environmental flow objectives for the lower Yellow River. The secondary intended readership is river managers from the Yellow River Conservancy Commission (YRCC). The report also contains information that could be of value to those with an interest in managing and using the lower Yellow River, and those seeking general advice on practical environmental flow assessments.

Environmental water requirements can be specified at a range of scales. At the basin planning scale, it is usually enough to know the mean annual environmental water allocation, while at the day-to-day river operation scale, it is necessary to know details about the target magnitude, duration, timing, frequency and rates of change of environmental flow components under a range of circumstances, such as during droughts or wet years. This report provides information to inform decisions at the day-to-day river operation scale.

This report is part of the Australia–China Environment Development Partnership (ACEDP) River Health and Environmental Flow in China Project (the project). The project established frameworks for assessing river health and environmental flows in China. The environmental flow framework was a generic framework to apply in locations such as the lower Yellow River, where the water resource is relatively scarce and, therefore, highly valuable, making river management issues complex and controversial. Other, simpler frameworks or approaches may be acceptable where water is relatively plentiful, demand relatively low, and environmental assets are not highly valued.

The framework established by the project takes an asset-based approach. Ecological asset-based policies focus on protecting key identifiable assets such as biodiversity, threatened species, native species, species of high conservation value, certain habitats, ecosystem services, or the relative health of ecosystems. The framework involves predicting the ecological health outcomes of a range of environmental flows scenarios.

The method used for the environmental flow assessment does not recommend a single environmental flow regime as being 'ideal' for the environment. The method derives a range of environmental flow options, with varying implications for meeting river health objectives and utilitarian objectives. The approach relies on balancing the flow needs of different users using input from water resources managers, together with other stakeholders as appropriate, using the science-based information provided by the environmental flows assessment. This entire process ultimately determines the environmental flow regime that will be implemented in a river.

Specification of flow components, particularly their magnitude, relies heavily on relationships between river hydraulics and river discharge. The hydraulic relationships are derived through modelling based on river morphology. These models, and the environmental flow options derived from them, are presented in a companion report, *Ecohydraulic Modelling and Flow Recommendations* (Gippel et al. 2012).

The report describes one component of the poject, which focused on the lower Yellow River. This section of the river was divided into four reaches, according to physical and ecological characteristics. The reaches selected were: Xiaolangdi to Gaocun; Gaocun to Taochengpu (Dawen River junction); Taochengpu to the estuary; and from the estuary to Bohai.

Information about flow-ecology and flow-geomorphology relationships was collected specific to these reaches through a literature and data review, aided by field visits to the assets for the Scientific Panel, hosted by local experts. The process for setting the environmental flow objectives was based around meeting the flow needs of the defined assets. The major assets were particular wetlands and the river channel, but within these major assets, other assets were identified at a finer scale. For example, species or communities, or physical and chemical processes, provide the wetland and river channel assets with their intrinsic conservation values, and their value in providing ecosystem services to society. These fine-scale assets can be evaluated with a framework that divides the ecosystem and its processes into the following linked categories: geomorphology, hydrology, water quality, waterbirds, fish, macroinvertebrates, and plants. The environmental flow objectives were derived from a conceptual understanding of flow-ecology, flow-geomorphology, and flow-water quality relationships. Some of these relationships are concerned with the lifecycle of biota, with specific hydraulic habitat requirements, or specific process requirements.

A number of flow-related issues have been recognised for the lower Yellow River:

- declining water availability
- sedimentation of the channel
- delta sediment balance
- reduction in extent and quality of riverine wetlands
- estuarine process alteration
- the water quality limits river health.

In response to these concerns, many environmental flow assessments have been undertaken on the lower Yellow River, using a range of methodologies. These studies have resulted in a range of flow recommendations. The flow records indicate that from 2000, when the Xiaolangdi Dam came into operation, the regulated flow has generally aligned with the flow regime recommended by Liu et al. (2006). Since 2004, the total flows have been within the target range most recently set by YRCC. The data suggests that since these environmental flow regimes were implemented, certain hydrological, geomorphological and water quality aspects of habitat have improved for river health.

In the lower Yellow River, water availability is a major limitation for environmental flows. The Yellow River is a working river of immense economic, social, and cultural value, so water for rehabilitation and maintenance of the river's important environmental values is scarce, and requires very careful use to maximise ecological health returns. Therefore, recommendations for environmental flows in the lower Yellow River are based on the premise that the future river health will not resemble a state that existed before the river was regulated for human use. Rather, the challenge for environmental flows assessment in the lower Yellow River is for the YRCC to consider a number of options, each with a different volume of water that is likely to result in a particular degree (or state) of river health. These options can then be traded off against the non-environmental demands, which also provide a range of societal benefits. This report does not specify environmental flow options; rather, the needs of the assets were assessed assuming unalterable physical constraints (such as presence of dikes and dams), and assuming the objective was a high level of stream health at low risk. The environmental flow options are detailed in the companion report, *Ecohydraulic Modelling and Flow Recommendations* (Gippel et al. 2012).

Of the potential flow components that comprise a river flow regime, baseflows, (preventing) cease to flow, bankfull flow, and high-flow recession were identified as being critical for the health of the lower Yellow River. Flow pulses were relevant to only a few objectives, and overbank flows were considered to be imprudent for this river. The low-flow period can be adequately managed by providing appropriate baseflows, but the summer/autumn high-flow period is more problematic.

The water-sediment discharge regulation (WSDR) for the high-flow period is entirely artificial, and is released from the Xiaolangdi Dam, although tributaries downstream of the dam can also make modest flood contributions to the Yellow River. The WSDR has positive benefits for channel morphology, lowered flood risk, inundation of the remaining riverine wetlands, watering the delta wetlands and generating favourable salinity conditions in the estuary. For operational reasons, it is preferable to release the water from late June, which is about a month earlier than the main flood period under pre-dam conditions. This timing does not create a major problem for the biota, but the water is 1–2 °C colder than pre-dam flows at this time of year, which could disadvantage some temperature-sensitive fish species that rely on the high flows for spawning.

The high-flow period flood peak is now of a shorter duration compared to the pre-dam situation. This may not be an issue for waterbirds, but the overall area of floodplain vegetation is reduced to lower floodplain terraces, and vegetation structure is therefore simplified. The current practice of rapid recession of the summer flood event may have negative consequences for waterbirds. Gradually exposed vegetation and mudflats in summer and autumn (June to November) are the main reason waterbirds use the riverine wetlands. Extending the duration of the flood recession could resolve the issue. In addition, a longer high-flow period that encompasses the full spawning and migration season of the fish community is likely be beneficial. However, implementing an extended flood recession would require a volume of water that exceeds the high-flow period allocation, and would drain water from the reservoir that would otherwise be delivered later for irrigation and other consumptive uses.

Although there are limitations on the extent environmental flows in the lower Yellow River can be improved for the benefit of river health, the detailed local flow-ecology, flow-geomorphology, and flow-water quality information contained in this report can provide a scientific foundation for refining current practice.

Chapter 1. Introduction

1.1 Background to this study

This report is a component of the Australia–China Environment Development Program (ACEDP) River Health and Environmental Flow in China Project, undertaken by the International Water Centre. The ACEDP is a five-year, Australian Government, AusAID initiative, with the objective of supporting and improving policy development in China in the area of environmental protection and natural resources management. The project will support those goals by strengthening China's approaches to assessing and monitoring river health, and assessing the river flows required for achieving ecological health.

The Yellow River study is one of three pilot sub-projects undertaken for the River Health and Environmental Flow in China Project. The Yellow River sub-project includes both a river health assessment and an environmental flows assessment. The main objective of the work is to trial and document approaches to river health assessment and environmental flows assessment that are applicable to the lower Yellow River specifically, and that also have potential for wider application in China.

1.2 Definition of environmental flows

Within a river, the 'flow regime' is the pattern of flows comprised of a variety of 'flow components'. Flow components are usually identified by their magnitude, their frequency and their duration, and by their role in supporting critical ecological and physical processes within the river corridor. Any flow regime will support a certain level of aquatic health. This applies to all rivers, regardless of whether specific environmental flow needs have been assessed. In this study, the term 'environmental flows' means *a flow regime*, fully specified through a scientifically-based process and associated with an expected level of river health. Thus, the term environmental flow refers only to a description of a flow regime (and associated water volumes). In any river, the environmental flow regime may occur naturally within the existing flow regime, it may be implemented artificially via dam releases, or it may be implemented by reducing extractions of water. It is assumed that an environmental flow regime will meet river-dependent needs of society to a certain, quantifiable degree.

The most common understanding of environmental flow, and the one adopted here, is that it is water that for the ecosystem and ecosystem-dependent human values of the riverine corridor (river channel and immediate floodplain, plus estuary), rather than water for off-stream environmental benefits. Examples of off-stream benefits are the benefits to catchment forests from rainfall and runoff before the water reaches a river, or benefits to urban parks and gardens from water diverted from a river. Irrigation is not a direct beneficiary of environmental flows because the supply of water to agriculture does not fundamentally rely on riverine ecosystems being healthy. The understanding adopted here is consistent with the *Brisbane Declaration on Environmental Flows*[1]:

> *Environmental flows describe the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems.*

The flow regime is only partly controllable in most rivers, and uncontrollable in others. In tightly flow-managed rivers, there are other considerations, apart from ecological considerations, to take into account in making decisions about how water resources will be allocated and managed. Flood control, irrigation water supply and domestic water supply must also be considered. Therefore, recommended environmental flow regime options are only one consideration to take into account when determining the actual flow regime of a river. An environmental flow regime is usually thought of as specifying the minimum flow that will sustain a given level of ecosystem health at a low level of risk – that is the 'agreed' ecosystem objective.

The term 'minimum flow' includes specifying baseflow magnitude and variability, the number and duration of flow pulses and floods, and the occurrence of cease to flow events in naturally intermittent streams. The regime may also be specified with upper limits on flows, because sometimes flows managed to suit non-environmental users are excessively high, or are aseasonal, relative to ecosystem requirements.

Environmental water requirements can be specified at a range of scales. At the basin planning scale, it is usually enough to know the mean annual environmental water allocation, while at the day-to-day river operation scale, it is necessary to know details about the target magnitude, duration, timing, frequency and rates of change of environmental flow components under a range of circumstances, such as during droughts or wet years. This report provides information to inform decisions at the day-to-day river operation scale.

1 The Brisbane Declaration of Environmental Flows proclaimed at the 10th International RiverSymposium and International Environmental Flows Conference, held in Brisbane, Australia, on 3–6 September 2007. Viewed 17 February 2010 at: http://www.nature.org/initiatives/freshwater/files/brisbane_declaration_with_organizations_final.pdf.

1.3 Environmental flow assessment method

The ACEDP River Health and Environmental Flow in China Project established frameworks for assessing river health and environmental flows (Gippel and Speed 2010a; Gippel and Speed 2010b; Gippel and Speed 2010c). The environmental flows framework (Gippel and Speed 2010b) sets out a generic approach to assessing the flow needs of specific rivers where the water resource is relatively scarce and, therefore, highly valuable, and river management issues are complex and controversial. The lower Yellow River is such a case. Other simpler approaches may be acceptable in situations where water is relatively plentiful, demand relatively low, and environmental assets are not as highly valued.

The method of environmental flows assessment used here is based on the framework proposed by Gippel and Speed (2010b). This framework accommodates:

- any form of environmental flow assessment
- any analytical tools
- any size river
- any existing constraints (regulated or unregulated, pre-existing allocation)
- any existing or proposed river uses
- any balance of scientific or social input to the process.

A detailed site-specific assessment would use all components of the framework, while a simpler assessment would only use a selection of the components. Omitting some components from the framework will still obtain a result regarding a recommended flow regime, but it will weaken confidence in achieving the expected outcomes and increase the risk of unexpected and unacceptable outcomes.

The first eight steps of the scientific input of the framework outlined in Figure 1 were originally derived from existing proven environmental flow methodologies for a study in Zhejiang Province, China (Gippel et al. 2009a; 2009b). The framework was loosely based around the FLOWS methodology as used in Victoria, Australia (SKM et al. 2002), which is a derivative of the Building Block Methodology (BBM) that was first developed in South Africa (Tharme and King 1998). The flow components of the BBM are also the foundation for the technical input to the DRIFT process, which was developed for a project in Lesotho, (King et al. 2003). A major difference between BBM and DRIFT is that DRIFT recombines flow components and their consequences to describe river conditions associated with any flow regime. BBM provides only one flow option, designed to meet a particular set of objectives. DRIFT also considers social impacts of each defined state of river condition. The methodology followed by Gippel et al. (2009a; 2009b) is similar to DRIFT in that it:

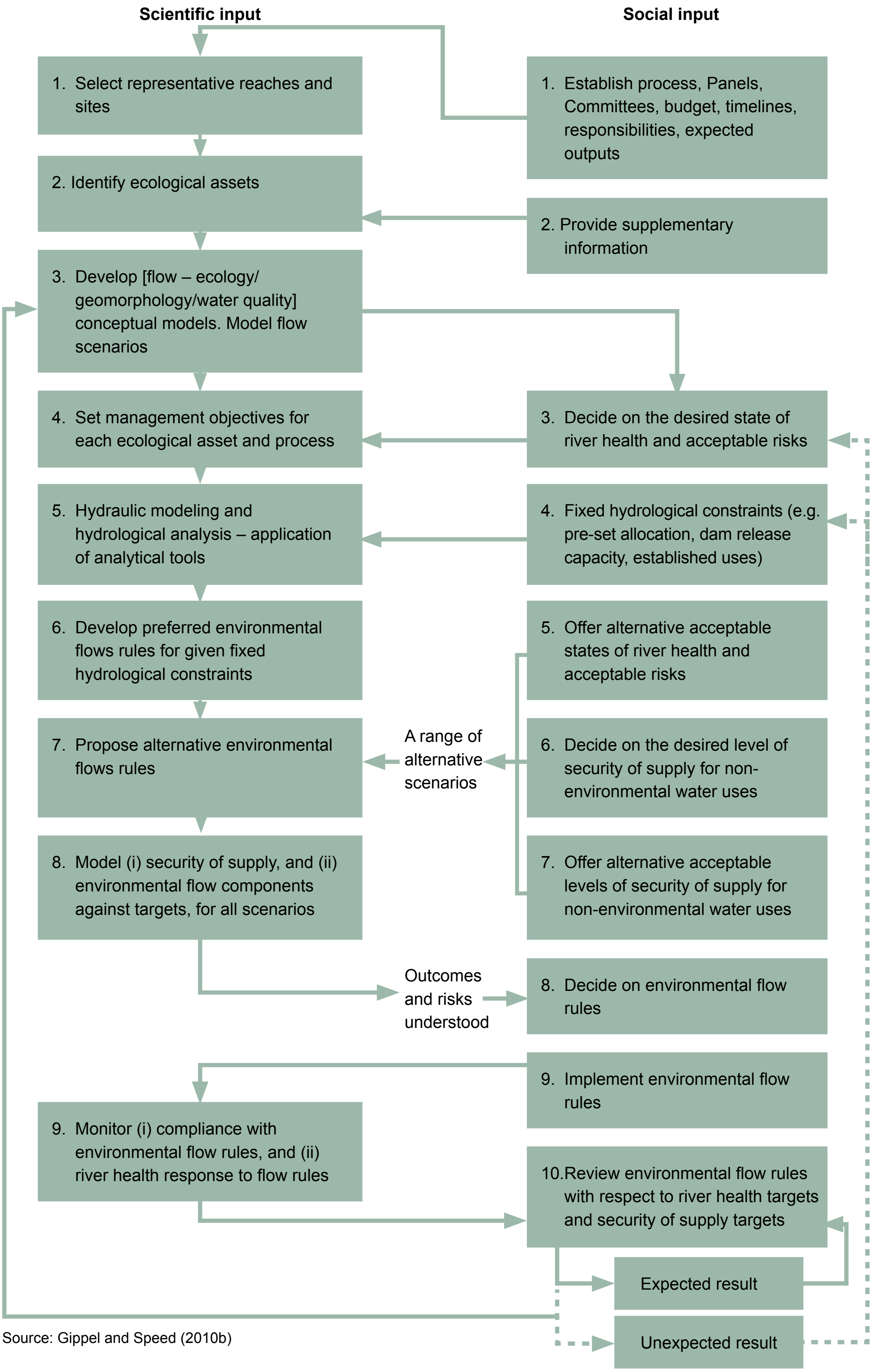
- generates a range of environmental flow options to analyse the implications of future flow scenarios for the environment and other users
- recognises that a flow regime comprises definable, ecologically important, flow components.

All these environmental flow methodologies belong to a group of approaches that are grounded on the 'natural flow paradigm'. The natural flow paradigm states that discharge variability, as found in natural rivers, is central to sustaining and conserving biodiversity and ecological integrity (Poff et al. 1997; Richter et al. 1997; Bunn and Arthington 2002). Discharge variability provides for biotic diversity, it influences life-history patterns, assists lateral and longitudinal connectivity (e.g. access to floodplains, and open upstream-downstream passage), and is less favourable for invasive exotic species (Bunn and Arthington 2002).

The suggested generic framework for environmental flow assessment in Figure 1 relies on five basic assumptions:

1. In most rivers, less than the natural flow will maintain ecosystem health at an acceptable level (or ecosystem values at acceptable risk), or there is water in rivers that can reasonably be used for non-environmental purposes.
2. Flow variability and the natural disturbance regime of a river are important for maintaining river health.
3. The flow regime can be characterised by a set of ecologically important flow components.
4. It is possible to describe, in isolation, the likely consequences for river health of not providing each important flow component, or not providing the flow components in their complete form.
5. Within the expectations of the river health status to be achieved by the environmental flow regime, river health is not limited by non-flow related factors, such as physical habitat (shelter and substrate); food supply; water temperature; water quality; direct exploitation of biota (such as fishing); barriers to movement; or direct disturbance to biota (e.g. gravel extraction).

Figure 1: Generic environmental flows assessment framework.



Source: Gippel and Speed (2010b)

For the fifth assumption, that river health is not limited by non-flow related factors, environmental flow assessments are usually undertaken to address current or future impacts of flow alteration on river health. An assessment may also be undertaken for rivers where non-flow related factors are the primary influence on river health. It is technically possible to address the other factors limiting river health through management actions. Achieving river health often requires simultaneous management action on many fronts. This is particularly the case for flow, because once flow is allocated to non-environmental uses, it is difficult and costly to recall it for environmental uses. Other limiting factors, such as water quality and physical habitat, can be improved at a later time without any serious impacts on the volumes of water available for non-environmental uses.

An environmental flow defines the important flow components of frequency, duration, timing, rate of change and inter-annual frequency. These specifications allow river managers to implement recommended flows as a comprehensive flow regime, either by directing controlled flows to a river, or by preventing inappropriate diversion of flows from a river.

The timing, frequency, duration of flows and inter-annual frequency relate to lifecycle needs of biota. The hydraulic conditions imposed by the rate of rise and fall of flows may encourage or discourage certain behaviours, or even disturb some organisms by exceeding their capacity to respond. Aquatic biota exists within a tolerable range of flow velocity and depth. These hydraulic parameters vary significantly with discharge. Access to certain physical habitat structures and locations (such as backwaters, tributaries, wetlands, floodplains and estuaries) also varies with discharge. For any given reach, variation in the hydraulic conditions is a function of discharge, controlled by the physical form of the river and its roughness elements (bed material, and in-stream large wood or vegetation). Therefore, the time series of available physical habitat is dependent on the hydrology and the physical form of the river. The physical form of the river is shaped by the pattern of flows combined with the supply of sediment and the relative resistance of the channel boundary to change. This is the rationale for adopting a combined hydrologic-hydraulic approach for the environmental flows framework. In rivers where water quality limits the biota, this impact also needs to be accounted for in the framework, as many water quality parameters vary as a function of flow.

The framework takes an asset-based approach to environmental flow assessment. Ecological asset-based policies focus on protecting key identifiable assets such as biodiversity, threatened species, native species, species of high conservation value, certain habitats, ecosystem services, or the relative health of ecosystems. Process-based policies focus on maintaining or restoring the physical, chemical and biological processes that sustain ecological assets. Examples of such processes are nutrient cycling, water flows, hydraulics, sediment dynamics, dispersal, adaptation, disturbance, and functional interactions. The framework suits an asset-based policy approach, and other methods may be required where different policy approaches are used. It is assumed here that scientists working within an asset-based policy framework would inevitably consider physical, chemical and biological processes when making environmental flow recommendations to protect or restore assets. Less obvious, but also important when working within the asset-based policy environment, is the need to consider the landscape context; the cumulative impacts of developments (local and catchment-wide); time lags between cause and effect; and possible long-term trajectories of hydrological and ecological change, whether natural or otherwise.

In common with all environmental flow methodologies, access to generic flow-ecology relationships is necessary, or site-specific relationships need to be developed. Riverine vegetation is often structured vertically, so site-specific flow-vegetation relationships can be developed from a model of the river's hydraulics. Particular habitats or locations where local hydraulics also determine access by biota to channels and floodplains can also be modelled. The hydraulic habitat preferences or tolerances are known for some key fish species, and these may be different for migration, spawning and recruitment periods. Information on biological requirements for timing, frequency, duration, rate of rise and fall, and inter-annual frequency is usually derived from information in the literature, hydrological characterisation of reference rivers (those supporting healthy populations), or characterisation of a period of the pre-disturbance flow record from the river of interest, if available.

The suggested generic framework involves predicting the ecological health outcomes of a range of environmental flows scenarios as outlined Figure 1. Predicting these outcomes will require continuous or stepped relationships to be developed between the hydrological characteristics of the flow components and ecological health, as proposed in the ELOHA framework (Poff et al. 2010). These relationships might be in the form of categories of risk to achieving a certain level of river health (e.g. Gippel et al. 2009b).

Balancing the provision of water for environmental flows against the provision of water for other users is undertaken using a water resources model. These models are capable of predicting flows anywhere in a system, and can also predict the effect of changing river management rules on the security of supply for off-stream water uses such as irrigation and urban demands.

This balancing process involves modelling a number of scenarios and reporting the results to stakeholders. It is up to the stakeholders to decide on the appropriate trade-off between river health and security of supply for non-environmental users of river water, via steps 3 to 7 of the 'social input' component of the framework shown in Figure 1. The trade-off should relate to the desired state of river health originally agreed in step 3 of the social input component of the framework. Any departure from that will need to be strongly defended.

Therefore, the method used here does not result in a single, ideal environmental flow regime. Rather, the method derives a range of environmental flow options, each with different implications for meeting river health objectives and utilitarian objectives. Balancing the flow needs of different users is undertaken by managers, together with other stakeholders as appropriate, using the science-based information provided by the environmental flows assessment. This is the process that ultimately decides the environmental flow regime that will be implemented in a river.

1.4 Objectives of this report

This report documents the scientific foundation for the environmental flow recommendations for the lower Yellow River. The primary intended readership is the Scientific Panel that is charged with the task of setting environmental flow objectives for the lower Yellow River. The secondary intended readership is the wider group of people with an interest in managing and using the lower Yellow River. The environmental flows framework followed here relies heavily on existing knowledge, so the comprehensive review of literature and data in this report will be a useful reference for anyone with an interest in the health of the lower Yellow River. This report also contains detailed information for those wishing to undertake similar environmental flow assessments in other rivers.

The report is structured to follow the main steps of the framework outlined Figure 1. The river was divided into reaches, and key ecological assets were identified. The flow issues that affect river health were then assessed. For the lower Yellow River, the existing river management vision and objectives were adopted.

There is a body of literature about the environmental flow needs of the lower Yellow River. Some of the existing recommendations were adopted and incorporated into the flow regime options in this study; others were revised as necessary.

There is also a wealth of documented knowledge about aspects of the lower Yellow River's hydrology, geomorphology, water quality and ecology. This knowledge, supported by new analysis of existing data, was used to derive the ecological flow objectives. This information was used to establish environmental flow objectives associated with the health of the identified ecological assets.

Specifying flow components, particularly their magnitude, relies heavily on relationships between river hydraulics and river discharge. The hydraulic relationships are derived through modelling based on river morphology. These models, and the environmental flow options that were derived from them, are presented in a companion report (Gippel et al. 2012).

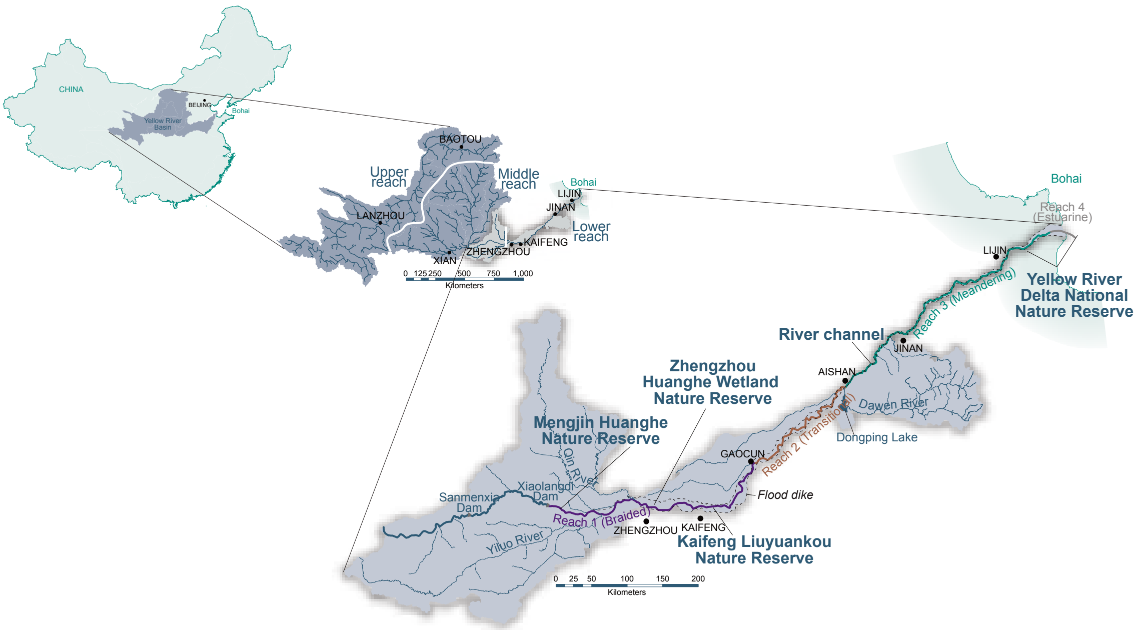
Chapter 2. Site and Assets

2.1 Yellow River Basin

The source of the Yellow River is in the Qinghai-Tibetan plateau of Qinghai province. The river then flows through seven provinces – Qinghai, Sichuan, Gansu, Shaanxi, Shanxi, Henan, and Shandong – and two autonomous regions – Ningxia and Inner Mongolia – before reaching its mouth at the Bohai. According to survey results in 1973, the Yellow River is 5464 km long with a basin area of 752,443 km^2. The watershed area is as large as 794,712 km^2 if the Erdos inner flow area is included (YRCC no date; Fu et al. 2004).

The Yellow River Basin is traditionally divided into the upper reach (above Hekou); middle reach (between Hekou and Huayuankou, or Taohuayu); and lower reach (below Huayuankou, or Taohuayu) (Ma et al. 2010; Yu, 2006) (Figure 2). The length of the river in the upper reach is 3471 km, in the middle reach is 1206 km and in the lower reach is 786 km[2] (Ye et al. 1999; Miao et al. 2010; Yu 2006). Annual mean precipitation in the upper basin is 368 mm, in the middle basin is 530 mm and in the lower basin is 670 mm (Miao et al. 2010). The basin is mostly arid and semi-arid land, and in the middle basin the river cuts through a loess mantle 100–200 m thick and 275,600 km^2 in area (Dungsheng 1985, as cited by Xu and Yan 2005). Around 76 per cent of the loess area suffers severe soil erosion (Wu et al. 2004).

Figure 2. Yellow River Basin, showing usual division of upper, middle and lower basin, the four reaches identified for environmental flow assessment, and the key ecological assets.



The Loess Plateau contributes around 90 per cent of the total sediment load of the Yellow River (Li 2003; Wang et al. 2008). The mean annual sediment load of the lower Yellow River is usually quoted within the range 1.0 to 1.6 × 10^9 tonnes[3], which supposedly ranks it first among the world's rivers for sediment load (e.g. Chen and Liu 1988; Li and Finlayson 1993; Li, 1994; Wu et al. 2004; Wang and Hu 2004; Wang et al. 2005; Zhou 2007). Wang et al. (2006) reported that the mean sediment load of 0.39 × 10^9 tonnes in the 1990s would place it fourth in the world, behind the Ganges-Brahmaputra, Amazon and Changjiang (Yangtze) Rivers[4]. The annual sediment load to the sea during the period 2000–2006 was only 0.15 × 10^9 tonnes, or 10 per cent of pre-2000 levels (Wang et al. 2010).

The average suspended sediment concentration is often quoted within the range 24 to 35 kg/m^3 (e.g. Zhang et al. 1990; Yu 2002; Wang and Hu 2004; Wang et al. 2005; Chu et al. 2006; Fan et al. 2006; Wang et al. 2010) and hyper-concentrated floods with sediment concentration over 100 kg/m^3 are not unusual. A sediment concentration of 911 kg/m^3 was measured on 7 September 1977 (Li and Finlayson 1993; Wang et al. 2005), and other instances of very high sediment concentrations were reported by Yu (2002). In terms of specific sediment yield, the average of 2480 t/km^2

2 This is the often-quoted length measured from Taohuayu, or Huayuankou Gauging Station, to the estuary. The river from Xiaolangdi Dam to the current mouth position, measured in this study along the meandering low-flow channel, was 840 km, which is similar to the estimated distance from Mengjin to the estuary by Yu (2006). Wang et al. (2005) cited a length of 876 km from Tiexie (near Mengjin), but this possibly related to a former river mouth position.

3 The mean sediment load to the sea recorded at Lijin over the period 1950 to 1999 was 0.8 × 10^9 tonnes (Wang et al 2010).

4 The Indus River also has a mean annual sediment load higher than this, according to data in Li and Finlayson (1993, Table 1).

quoted by Shi and Shao (2000) or 2,280 t/km^2 quoted by Xu and Yan (2005), would place it highest of any major river system in the world. Although different values of mean sediment load and concentration for the large rivers of the world can be found in the literature (e.g. Yu, 2002; Fu et al. 2004), the Yellow River certainly ranks highly among them, even after recent declines in sediment load. Although the sediment load of the Yellow River is high by world standards, because it drains a largely temperate semi-arid catchment, its water yield is not particularly high by world standards, ranking seventh in China (Xie and Chen 1990).

In 2000, the population within the Yellow River Basin was about 110 million (Miao et al. 2010), by 2006 it had reached about 113 million, and it was projected to be 120 million by 2030 (Miao et al., 2010, citing a YRCC estimate from 2002). In addition, irrigation districts located outside the dikes that use water diverted from the Yellow River have a population of around 55 million (Fu et al., 2004, citing YRC, 1999). The catchment includes 12.6 million ha under agriculture, of which 40 per cent is irrigated with water sourced from the Yellow River (Xia et al. 2002). Water use in the Yellow River Basin is currently considered to come from ground sources and surface sources, and it serves three sectors: agriculture, industry and domestic (Giordano et al. 2004). In the period 1998–2000, 74 per cent of water used in the basin was from surface water and 26 per cent was from groundwater. Agriculture is by far the largest user of water in the basin, accounting for 80 per cent of the total withdrawal (Giordano et al. 2004). In 2000, 76 per cent of the available water resource was taken for human uses, 10 per cent entered the sea, and 14 per cent was lost to evaporation, interaction between groundwater and deep aquifers, or other unaccounted losses (Giordano et al. 2004). Therefore, the water resource is relatively scarce, creating a tension between allocating water for the benefit of river health, and allocating water for direct social and economic benefit.

An environmental flow assessment for the Yellow River is a high priority given:

- the relative scarcity of the basin's water resources
- the basin's apparently declining water resources
- problems associated with large sediment loads, including flood risk
- the high value of some river-dependent ecological assets, including Ramsar and nationally important wetlands
- the high demand for water by the basin's large population and extensive irrigation areas.

In most water-stressed river systems, the tension between water users is greatest in the lower reaches. This is because (i) the lower reaches suffer the effects of upstream withdrawals (ii) the lower reaches are generally the most populated parts of catchments and (iii) lowland floodplains and river estuaries are often considered to have relatively high ecological value, because of their intrinsic value and because development has reduced their size. This is the case for the Yellow River; therefore it is appropriate that this report focuses on the lower Yellow River as the area of most immediate concern.

2.2 Lower Yellow River

2.2.1 Basic physical and social characteristics

The lower Yellow River begins were the river emerges from the foothills of the highly erodible Loess Plateau onto a vast alluvial fan, known as the North China Plain. The river flows across the plain for a distance of around 840 km and enters the Bohai near Dongying. In most of the literature, the beginning of the lower river is marked at Huayuankou, which is the location of an important hydrological gauging station. However, morphologically, the lower river begins a short distance upstream of Huayuankou near Mengjin. Since late 1999, the flow of the lower river has been largely controlled by the Xiaolangdi Dam[5], located about 128 km upstream of Huayuankou, so this dam represents the hydrological beginning of the lower Yellow River.

The lower Yellow River has a relatively small local catchment area, with just a few tributaries. Flood dikes constructed along the entire course of the lower Yellow River (except where it abuts valley walls) have severed the natural hydrological connection between the river and the North China Plain. The flood dikes have been in place for many centuries. Vast amounts of sediment are delivered from the Loess Plateau in the middle Yellow River area, and deposition of this material has created a suspended floodplain within the diked section that, for most of the river's course, is 3–10 m higher than the land outside the dikes. Sediment reaching the sea has created a vast, morphologically and ecologically dynamic, delta landform.

The lower reach of the Yellow River runs through two provinces: Henan (upstream) and Shandong (coastal area). The river provides water for a large area of irrigated agriculture, and also for domestic and industrial supply, including the Shengli Oilfield, the second largest oilfield in China (Chen et al. 2007), located on the delta.

5 Xiaolangdi is a multi-purpose Dam that was completed in October 1999; its functions are flood control, ice-jam prevention, sediment control, power generation, flow regulation for irrigation, and domestic and industrial water supply. The Dam wall is 154 m high and the Dam has a total capacity of 126.5 × 10^8 m^3. The power plant's capacity is 1836 MW, generating 5.1 × 10^9 kWh of electricity per year.

Before 1949, floods on the lower Yellow River caused, on average, two river breaches every three years and one river course change every 100 years (Li and Finlayson 1993; Zhu et al. 2003). The flood dikes now contain a flow of 22,600 m^3/s (ADB, 2001), which corresponds to the peak flow at Huayuankou in the flood of 1958. Li and Finlayson (1993) estimated that at Huayuankou, the peak discharges of floods with 10,000, 1000 and 100-year recurrence intervals were 55,600 m^3/s, 42,300 m^3/s and 29,300 m^3/s, respectively. Note that the Xiaolangdi Dam reduced the magnitudes of floods for these return intervals. In the event of a major flood with a dike breach, an area of 49,000 km^2 is at high risk of inundation (ADB 2001). This area has a population of 32.8 million, of which 28.8 million are in the agricultural sector and are particularly vulnerable to the effects of floods. The inner floodplain zone (within the flood dikes), which coincides with 85 per cent of the lower river catchment area (4,647 km^2), has a population of 1.7 million[6] residents living in 2,193 villages. The inner floodplain is relatively densely populated (431 persons/km^2) and highly vulnerable to floods (ADB 2001).

The most recent large flood in the lower Yellow River occurred in 1998. This flood affected 7.33 million houses, caused 3656 deaths, affected 25 million hectares of farmlands, resulted in monetary losses estimated at RMB 248.4 billion (USD 30 billion equivalent) and reduced gross domestic product (GDP) by 3–4 per cent (ADB 2001). Two years before, a flood affected 5.12 million houses, caused 4400 deaths, impacted 31 million hectares farmland, resulted in monetary losses of RMB 220.8 billion (USD 26.7 billion), and reduced GDP by about 4 per cent (ADB 2001).

2.2.2 Ecological assets

Rivers contain ecological assets in two main categories:

- intrinsic ecological assets
- ecosystem services provided by natural assets.

These two categories of assets are equivalent to the two functions of rivers described by Liu et al. (2006): natural function and social function. Intrinsic ecological assets are defined in terms of conservation values, with the most important, or 'key' assets usually considered as those with the highest conservation value. Sometimes, key assets are publicly identified by, for example, Ramsar listing, or listing as nationally or regionally important, rare, unique, representative or threatened assets. Other ecological assets might be regarded as important because they play a key role in ecosystem function. Ecological assets can be locations, species, or functions and processes. Ecological functions are physical, chemical and biological processes that support the ecological assets.

Natural assets, some of which might be considered key ecological assets, provide ecosystem services that are of direct economic benefit to society. Ecosystems can be considered a renewable resource that produce surplus, or harvestable goods, such as sufficient fish abundance and diversity to support an economically viable fishery, water for drinking, food, timber, and livestock production. Examples of other utilitarian benefits are groundwater recharge, sediment and nutrient cycling, cultural values, navigation, and recreation and tourism opportunities. Liu et al. (2006) took the view that the social function of providing ecosystem services was '…the original intention and meaning of maintaining the healthy life of rivers', but accepted that the ecological health of rivers ultimately affected social and economic river functions. The focus of this environmental flows assessment is on intrinsic ecological assets. It is assumed here that when ecological assets are in a healthy state they also provide ecosystem services.

The key location-based assets identified in this study include the river channel itself; three riverine wetland reserves (Mengjin, Kaifeng and Zhengzhou); a large lake (Dongpinghu) and the delta wetland reserve. We added to this list a national nature reserve that is associated with the lower Yellow River, but which lies outside the main flood dike (Yubei), and the intertidal zone around the Yellow River Estuary and the Bohai, which supports an important fishery. The riverine wetlands are provincial or national-level nature reserves and have been listed as Important Bird Areas (IBAs) that contain areas that would qualify as Ramsar sites (Birdlife International, 2005; http://www.birdlife.org/datazone/). These types of riverine wetland are uncommon in the lower Yellow River, as most of the riparian wetlands have become disconnected through: construction of physical barriers (dikes); flow regulation, which has reduced the frequency and duration of hydraulic connection; and land use change, such as direct conversion of native vegetation to cropland. Defined as specific locations, there are eight key ecological assets in the lower Yellow River:

1. the river channel from Xiaolangdi Dam to the Bohai
2. Mengjin Huanghe Nature Reserve
3. Zhengzhou Huanghe Wetland Nature Reserve
4. Yubei Huanghe Gudao Nature Reserve
5. Kaifeng Liuyuankou Nature Reserve
6. Dongping Hu
7. Yellow River Delta Nature Reserve
8. intertidal zone around the Yellow River Estuary and the Bohai.

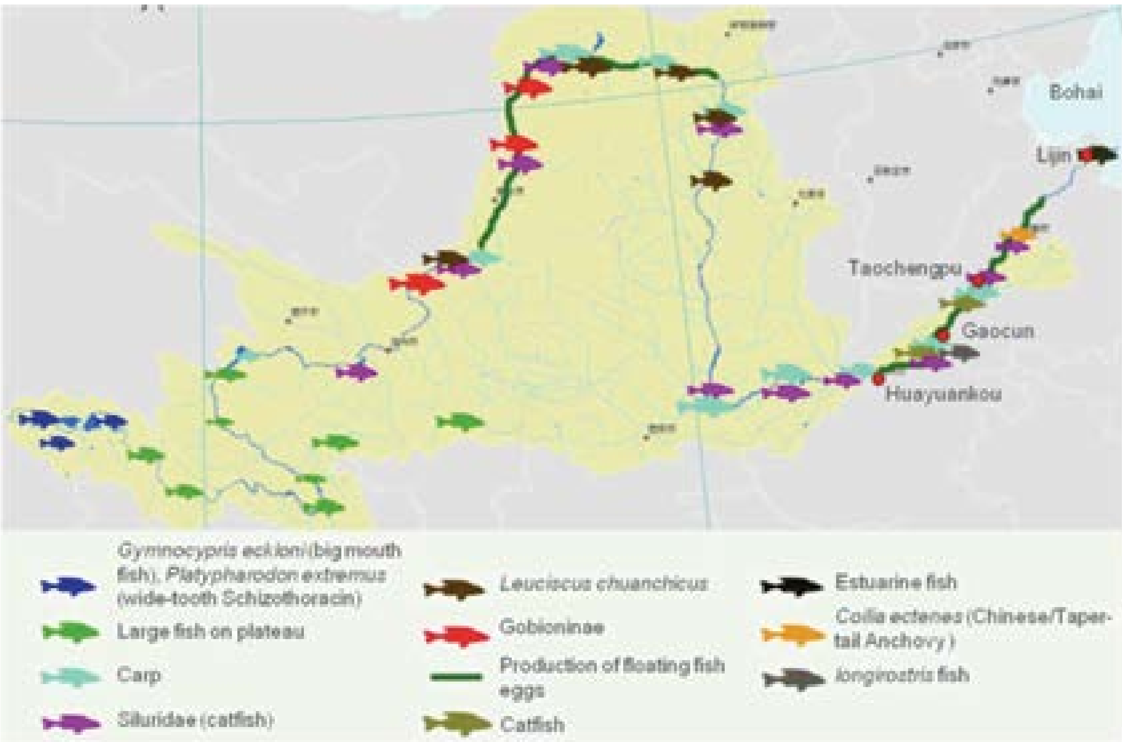
6 Yu (2006) gave a 1996 population estimate of 2 million residents within the dikes. The date of the ADB (2001) population estimate is unknown.

The lower Yellow River also has ecological assets in the form of important species and communities of waterbirds, fish, macroinvertebrates and plants, plus the ecosystem functions that support them. These are all represented in the eight locations listed above. In the past, the Yellow River supported a commercial fishery, but at the present time there is no commercial fishery in the river, although the Bohai, into which the Yellow River flows, remains one of the most important fishery resources in China.

The Yellow River channel from Xiaolangdi Dam to the Bohai

The river channel is included as an asset because it provides longitudinal and lateral continuity for transfer of carbon, sediment, nutrients and contaminants, and also provides a passage for migration of fish or drift of invertebrates and floating fish eggs (Figure 3). The channel is also the physical structure within which hydraulic habitat becomes available under the right flow conditions (i.e. areas of particular depth, velocity and substrate that are suitable for the biota to complete their life cycles). The main stem of the Yellow River throughout the entire basin has historically provided important spawning sites for fish, with the lower reaches being particularly important for *Coilia ectenes* (Chinese/taper-tail anchovy), carp and various catfish (Figure 3).

Figure 3. Historical fish spawning sites in the main stem of the Yellow River. Source: Zhang Jianjun, Yellow River Fisheries Research Institute, Chinese Academy of Fishery Sciences.



Mengjin Huanghe Nature Reserve

Central coordinates: 34°52'N 112°30'E

Mengjin Huanghe Nature Reserve is situated in the northeast of Mengjin County. The reserve was established as a provincial-level nature reserve in 1995. The reserve is incorporated into Henan Yellow River Wetland National Nature Reserve (68,000 ha), which was established in 2003. The Mengjin Huanghe Nature Reserve is 28 km long and 0.5–5.0 km wide. Covering a total of 15,000 hectares, the reserve consists of three parts: the core area (4500 hectare), the buffer area (3500 hectare) and the experimental area (7000 hectares). The reserve has recorded 166 bird species, of which 95 are waterbirds (BirdLife International, 2009).

Threatened bird species are: oriental stork *Ciconia boyciana* (endangered or EN); swan goose *Anser cygnoides* (EN); lesser-white-fronted goose *Anser erythropus* (vulnerable or VU); Baer's pochard *Aythya baeri* (VU); and great bustard *Otis tarda* (VU, 52 birds in 1998) (BirdLife International, 2009).

Congregatory waterbirds are: *Anser fabalis*, *Tadorna ferruginea*, *Anas poecilorhyncha*, *Anas platyrhynchos*, *Grus grus* (BirdLife International, 2009).

Criteria for determining IBA are:

- A1: Globally threatened species: the site is known or thought regularly to hold significant numbers of a globally threatened species, or other species of global conservation concern.
- A4i: Site known or thought to hold, on a regular basis, 1 per cent of a biogeographic population of a congregatory waterbird species.
- A4iii: Site known or thought to hold, on a regular basis, 20,000 waterbirds or 10,000 pairs of seabirds of one or more species.

An investigation by Ma et al. (2008) of waterbirds in Mengjin between 1995 and 2008 found 98 species of waterbirds, belonging to 18 families and eight orders. Of the species found, two were national first-grade protected wildlife in China, and 12 species were second-grade. As a fauna distribution, 63 species belonged to Palearctic, five to the Oriental realm and 30 were widespread.

Changes in hydrology and land use, mainly since the Xiaolangdi Dam began operation in late 1999, mean that only small fragments of the original extensive riverine wetland remain. The predominant plants include *Typha angustifolia* Linn, *Scirpus triqueter* Linn, and *Phragmites communis Trin* Linn (Zhao et al. 2009; Zhao et al. 2011; Xu et al. 2011).

Zhengzhou Huanghe Wetland Nature Reserve, or Huanghe Shidi National Nature Reserve

Central coordinates: 34°54’N, 113°40’E

Established in 2004, Zhengzhou Huanghe Wetland Nature Reserve is located between the middle and lower reaches of the Yellow River. Covering 38,007 hectares, the reserve is 158.5 km long and 23 km wide. The reserve includes 2055 ha of forest, 7352 ha of agricultural land, 19,000 ha of beaches, 9500 ha of open water, and about 100 ha of artificial ponds. There is human activity throughout most of the nature reserve (BirdLife International, 2009).

Threatened bird species are: Siberian crane *Grus leucogeranus* (CR); oriental stork *Ciconia boyciana* (EN); red-crowned crane *Grus japonensis* (EN); Dalmatian pelican *Pelecanus crispus* (VU); Pallas’s sea eagle *Haliaeetus leucoryphus* (VU); greater spotted eagle *Aquila clanga* (VU); eastern imperial eagle *Aquila heliaca* (VU); hooded crane *Grus monacha* (VU); and great bustard *Otis tarda* (VU) (BirdLife International, 2009).

Congregatory waterbirds are: *Anser fabalis*, *Tadorna ferruginea*, *Anas platyrhynchos*, *Anas poecilorhyncha*, *Grus grus* (BirdLife International, 2009).

Other fauna include: 217 recorded species of land vertebrates, including *Lutra lutra* (otter) (BirdLife International, 2009).

IBA criteria are:

- A1: Globally threatened species: the site is known or thought regularly to hold significant numbers of a globally threatened species, or other species of global conservation concern.
- A4 i: Congregations: Site known or thought to hold, on a regular basis, 1 per cent of a biogeographic population of a congregatory waterbird species (BirdLife International, 2009).

From December 2004 to September 2009, the bird resources in Zhengzhou Huanghe Wetland Nature Reserve were systematically investigated by Li et al. (2010). A total of 15 orders, 36 families, and 115 bird species were recorded. Li et al. (2010) were of the opinion that the diversity of birds was increasing at this site, and attributed this increase to temperature rises associated with global warming. One significant change in this respect was the spread of some Oriental realm birds northwards to Zhengzhou, with the change occurring around 1990.

Another bird survey in Zhengzhou wetlands conducted by Niu et al. (2008) between September 2006 and August 2007 found 247 species belonging to 53 families and 16 orders. Avian diversity was highest in the low-lying wetlands close to the river. Two hundred and seventeen species of land vertebrates have been recorded in the reserve including the Eurasian otter *Lutra lutra*.

Yubei Huanghe Gudao Nature Reserve

Central coordinates: 114°7'N 35°24'E

Yubei Huanghe Gudao Nature Reserve was established as a provincial-level nature reserve in 1988 and upgraded to a national nature reserve (24,780 ha) in 1996. The nature reserve is divided into two sections: one located where Weihui City meets Yanjin County and the other a mudflat in Fengqiu County, with areas of 10,500 ha and 14,280 ha respectively. Both sections are wetlands north of the lower Yellow River, 41 km apart (BirdLife International, 2009). While these wetlands are associated with the lower Yellow River, they are located on the plain about 20 km outside the main flood dike, so are not a critical asset with respect to the flow regime of the Yellow River.

Thirteen threatened species are recorded in the reserve: Siberian crane *Grus leucogeranus* (CR); oriental stork *Ciconia boyciana* (EN); swan goose *Anser cygnoides* (EN, 412 birds in 1991); red-crowned crane *Grus japonensis* (EN), Dalmatian pelican *Pelecanus crispus* (VU); lesser-white-fronted goose *Anser erythropus* (VU, 250 birds in 1991); Baikal teal *Anas formosa* (VU); Baer's pochard *Aythya baeri* (VU); greater spotted eagle *Aquila clanga* (VU); lesser kestrel *Falco naumanni* (VU); white-naped crane *Grus vipio* (VU); hooded crane *Grus monacha* (VU); great bustard *Otis tarda* (VU); and one congregatory species (lesser white-fronted goose *Anser erythropus*) (BirdLife International, 2009).

Kaifeng Liuyuankou Nature Reserve

Central coordinates: 34°54'N 114°29'E

Established as a provincial-level nature reserve in 1994, Kaifeng Liuyuankou Nature Reserve is located in eastern Henan, 10 km north of Kaifeng City. Covering 16,148 ha, the reserve extends 60 km from east to west and 15.5 km from north to south. Within the nature reserve, the banks of the Yellow River are 10–20 km apart (BirdLife International, 2009).

Threatened species are: Siberian crane *Grus leucogeranus* (CR, 43 birds in 1991); oriental stork *Ciconia boyciana* (EN); swan goose *Anser cygnoides* (EN, 255 birds in 1993); red-crowned crane *Grus japonensis* (EN); lesser-white-fronted goose *Anser erythropus* (VU); Baikal teal *Anas formosa* (VU); Baer's pochard *Aythya baeri* (VU); white-naped crane *Grus vipio* (VU); hooded crane *Grus monacha* (VU); and great bustard *Otis tarda* (VU). Congregatory waterbirds are: *Anser erythropus* and *Grus grus* (BirdLife International, 2009)

The characteristics of the site that meet IBA criteria are:

- A1: Globally threatened species: the site is known or thought regularly to hold significant numbers of a globally threatened species, or other species of global conservation concern.
- A4 i: Congregations: Site known or thought to hold, on a regular basis, 1 per cent of a biogeographic population of a congregatory waterbird species (BirdLife International, 2009).

Dongping Hu

Central coordinates: 35°58'4.3"N 116°11'45.1"E

Dongping Hu is the second largest freshwater lake in Shandong Province (Dou et al. 2000). The lake was once a very important location for spawning of a high-value fish, *Coilia ectenes* (estuarine tapertail anchovy). The lake is currently designated as a potential flood detention basin (Sun et al. 2007), but only for very large floods, such as the flood that occurred in 1982. The lake is disconnected from the Yellow River by a regulator during low-flow periods. Dongping Hu is included here because of its potential role in restoration of *Coilia ectenes*.

Dongping Hu is divided into two components, based on its operation: the new lake and the old lake. The new lake covers an area of 418 km^2 with a storage capacity of 2.367 x 10^9 m^3. During normal operations, there is no water in the new lake; it is designated for storage under major flood conditions only. The old lake, covering an area of 209 km^2 with a storage capacity of 1.194 x 10^9 m^3, is inundated year round. The lake connects with the Jing-Hang Grant Canal, the Yellow River, Wenhe River, East Route of the South North Water Transfer Project and Jiaodong Water Transfer Project of Shandong, forming a radial water network with Dongping Hu as the centre (Sun et al. 2007).

Dongping Hu is an important storage used to help regulate the water resources of the lower river, supplement the basic water required in the Yellow River for ecological purposes, provide flows to help scour the riverbed and improve the channel morphology, provide water to dilute or reduce pollution, and replenish water for industry, agriculture and domestic use of the lower reaches of the Yellow River (Sun et al. 2007).

Yellow River Delta National Nature Reserve

Coordinates: 37°35’N to 38°12’ N 118°33’ E to 119°20’ E

The Yellow River Delta Nature Reserve is an internationally important wetland situated in the north-east of Dongying City, Shandong Province. The reserve was established in 1992 by the State Council of China, Ramsar listed in 1994, and listed as a National Demonstration Reserve in 2006. The reserve has two parts: the southern part is located at the current estuary of the Yellow River and the northern part, which has an area of 48,500 ha, is located at a former estuary that was cut off from the river in 1976. The total area of the reserve is 153,000 ha of which 79,000 ha is core area, 11,000 hectares is buffer area, and 6.3 ha is experimental area. As new land is created by progradation of the delta it is added to the reserve.

There are 131 km of coastline in the nature reserve, with irregular and semi-diurnal tide. The mean spring range is 1.06–1.78 m and the neap range is 0.46–0.78 m. Sea ice usually begins to occur by the end of December and thaws in early March. The reserve is mainly marine and coastal wetlands, including 31,314 ha of marine waters, 38,534 ha of intertidal mudflat and 32,772 ha of intertidal reed marshes, providing critical stopover habitat for migratory waders (Barter 2002). However 7966 ha of inland or man-made wetlands, including permanent rivers and streams, fresh water ponds and reservoirs, are dispersed in the terrestrial area (Chen et al. 2007).

With its vast area, abundant wetland vegetation and aquatic organisms, as well as sparse human population, the reserve provides habitat for breeding, migration and wintering birds. In light of the species and numbers of birds living in different types of vegetation, six kinds of habitats can be identified in the reserve, including farmland and reed ditches, forest, reed and meadow wetlands, salt bush marshes, water areas and *Suaeda* mudflat (Chen et al. 2007).

As it is a newly developed wetland ecosystem, the 393 plant species of the reserve are of great scientific and conservation significance, among which wild soybean (*Glycine Soja* sieb.et Zucc) is a threatened species (Chen et al. 2007).

The diversity of habitat types and extensive areas of wetlands within the Yellow River Delta wetland complex support at least 265 bird species (Chen et al. 2007). There are seven bird species of the reserve that are listed as National Class 1 Priority, including red-crowned crane (*Grus japonensis* EN); great bustard (*Otis tarda dybowskii* VU); white-tailed eagle (*Haliaeetus albicilla*); golden eagle (*Aquila chrysaetos daphanea*); white stork (*Ciconia ciconia boyciana* EN); hooded crane (*Grus monacha* VU); and scaley-sided merganser (*Mergus squamatus* EN), and 33 bird species that have been listed as National Class 2 Priority. The delta provides habitat for 11 species that congregate in large flocks (*Ciconia boyciana, Cygnus cygnus, Anser fabalis, Anser albifrons, Anser anser, Anas platyrhynchos, Grus grus, Grus monacha, Grus japonensis, Fulica atra, Saundersilarus saundersi*) (BirdLife International, 2009). Seven species have been listed in Appendix 1 of the Convention on the International Trade in Endangered Species (CITES), including the white stork (EN), white-tailed eagle, red-crowned crane (EN), hooded crane (VU), white-naped crane (*Grus vipio*), little curlew (*Numenius minutus*) and Nordman’s greenshank (*Tringa guttifer* EN), while 26 have been listed in Appendix 2 and 7 bird species have been listed in Appendix 3 or the Convention. In the Sino–Japanese Agreement on the Protection of Migratory Birds and Their Habitats, the Yellow River Delta Nature Reserve has 152 species, constituting 67 per cent of the total 227 species. For the Sino–Australia Agreement on the Protection of Migratory Birds and Their Habitats (CAMBA), 51 species have been found in the reserve, accounting for 63 per cent of the total 81 species. The region provides critical wintering habitat for a range of species such as ducks and swans, red-crowned cranes and Eurasian cranes and is probably the most important wintering ground of the great bustard in eastern Asia. The region is also important as a foraging site for a diverse range of migratory species including shorebirds, cranes such as the red-crowned and white-naped cranes (Higuchi 2004), and storks. It also provides important breeding habitat for a diverse range of summer migrants and resident species (grebes, herons and gulls). In addition to birds, several species of marine mammals, reptiles and fishes have also been listed into CITES appendices or national priorities (Chen et al. 2007).

Intertidal zone around the Yellow River Estuary and the Bohai

The 2.0 to 2.5 m average tidal range on the western side of the Bohai (Xu et al. 1996) exposes an intertidal area of 3700 km^2 (Barter 2002). This region provides critical foraging habitat for migrating shorebird species. A total of 36 shorebird species have so far been found to occur in internationally important numbers at one or more sites in the Yellow Sea (Barter 2002), representing 60 per cent of the migratory shorebird species in the East Asian–Australasian Flyway (two globally threatened: spotted greenshank (EN) and spoon-billed sandpiper (VU), and two near-threatened: eastern curlew and Asian dowitcher). The Yellow River estuary provides foraging habitat for more than 20 per cent of flyway populations of Eurasian curlew and Kentish plover and more than 10 per cent of flyway populations of little curlew and grey plover (Barter 2002). The Yellow River Delta area supports 17 shorebird species of international importance (16 north migration, five south migration), with over 130,000 shorebirds on northward migration (Barter 2002).

As the key assets are distributed along the lower Yellow River, it is important to specify the environmental flow needs for locations in vicinity of the assets, as there is no guarantee that a single set of recommendations for the river mouth will ensure that the flow needs of the assets located between Mengjin and Lijin are met. This means that the flow recommendations for the lower Yellow River need a number of compliance points.

2.2.3 Reaches and sites for assessment

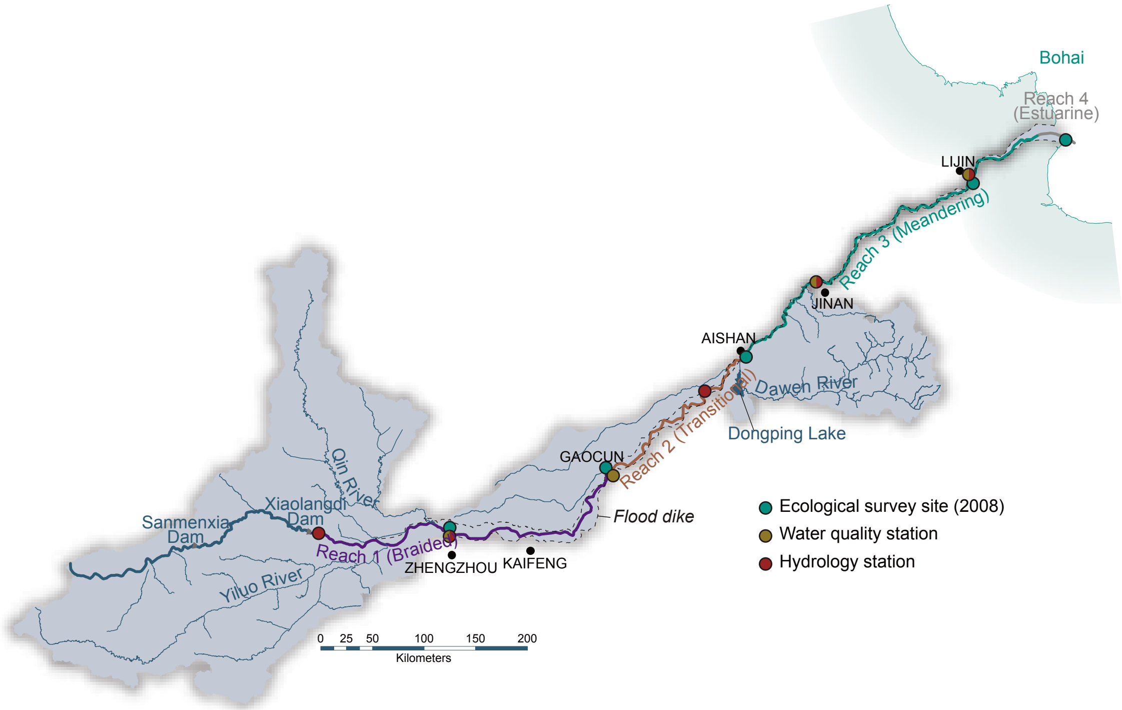
In environmental flows assessment, the river under investigation is usually divided into a number of reaches that are reasonably heterogeneous for one or more ecological, hydrological, geomorphological and water quality attributes, and location of assets. The division into reaches simplifies the river, and allows different assessments to be made for different parts of the river in a structured way. The process produces a set of recommendations for each reach. Compliance of the actual flow regime against the recommended environmental flow regime is checked at gauging stations. If delivery of a certain flow regime is required for an asset that is essentially a local point, then the gauge for checking compliance is ideally situated upstream of the asset. If the asset is located along an entire reach, then the gauge for checking compliance is ideally located at the downstream end of the reach.

The lower Yellow River was divided into four reaches for environmental flows assessment. For this project, an existing reach division, based on geomorphological characteristics, was slightly modified to suit the project objectives, as shown in Figure 4. A number of authors have previously used the original division (Xu 2003; Wang and Hu 2004; Xu 2005b; Wu et al. 2005; Yu 2006; Xia et al. 2008; Wu et al. 2008a), with most reproducing the same map (Wu et al. 2005; Yu 2006; Xia et al. 2008; Wu et al. 2008a). The only attribution to the original source appears to be that by Wu et al. (2005) to Qian et al. (1993). The beginning of the lower Yellow River is referred to both as Mengjin (Yu 2006; Xia et al. 2008) and Tiexie (Wang and Hu 2004; Xu 2005b; Wu et al. 2005). These places are in close proximity, located just downstream of Xiaolangdi Dam. Wu et al. (2008a) used Taohuayu as the beginning, which is located just upstream of Huayuankou near the Qin River junction, and Xu (2003) used Huayuankou as the beginning. In this project, the beginning of the lower Yellow River was set as the reach downstream of Xiaolangdi Dam.

The estuary is a distinct reach of the river, because it is affected by saline water and tides from the Bohai and contains the Delta National Nature Reserve asset. The upstream extent of the estuary depends on flow conditions, but because the tide at the Yellow River estuary is weak and the tidal range is small, the estuarine tidal limit extends about 17 km upstream in dry season and about 9 km in flood season, and the tidal current reach ranges from 4–7 km upstream in the dry season to 0–6 km in the flood season (Hu et al. 1996; Li and Wang 2003; Chu et al. 2006; Sun and Yang, 2010). The tidal currents intrude only 2–3 km when the discharge is 1000 m^3/s, and no intrusion takes place when the discharge is more than 2000 m^3/s (Fan et al. 2006). The depth-averaged velocity of the flood current is usually larger than that of the ebb current, and the maximum flood velocity in the delta front reaches 2.2 m/s (Fan et al. 2006).

Most of the authors who have used the four-reach geomorphological zoning have extended the estuary reach to Lijin. However, Lijin is 104 km upstream from the river mouth (Yu, 2006), which is well beyond the reach of the tidal effects or saline water. In this study, the estuarine reach division was set at approximately 20 km upstream of the mouth, as shown in Figure 4.

Figure 4. Lower Yellow River, showing four reaches used in environmental flow assessment, and location of gauging stations used for water quality and hydrological analysis.



There are few natural inflows to the lower Yellow River, although the Dawenhe and Wenhe systems flow to Dongping Hu, which is partially connected to the Yellow River. With an annual average runoff for the period 1952–2001 of 10.6 $\times 10^8 m^3$, the Wenhe is the major source of water to Dongping Hu (Sun et al. 2007). The channel leaving Dongping Hu is Xiaoqinghe, flowing for about 5.6 km to join the Yellow River near Aishan. As the reach between the estuary and Dongping Hu was once an important migration route for *Coilia ectenes*, and because the river changes from transitional to meandering geomorphological planform (Figure 4), the junction of Xiaoqinghe (near Taochengpu) is a natural reach boundary.

Gaocun marks the boundary between the upper braided channel form and a transitional form (Figure 4). Upstream of Gaocun to Mengjin is the braided reach (Figure 4). This reach contains Mengjin, Zhengzhou and Kaifeng Liuyuankou Nature Reserve assets. Before the Xiaolangdi Dam was constructed, Mengjin marked a significant geomorphological boundary, but the dam now forms a major hydrological boundary, so the short steeper section of river from Xiaolangdi to Mengjin was included in the upper braided reach.

The reaches selected for this study were:

1. Xiaolangdi to Gaocun
2. Gaocun to Taochengpu
3. Taochengpu to the estuary
4. Estuary to Bohai.

Information about flow-ecology and flow-geomorphology relationships was collected specific to these reaches. This was done through a literature and data review, aided by field visits to the assets by the Scientific Panel that were hosted by local experts.

Chapter 3. Environmental Flows Issues and River Management Policy Framework

3.1 Flow-related issues affecting river health

Several major flow-related issues have been identified that impact the ecological health of the Lower Yellow River.

Declining water availability

Since the founding of the People's Republic of China in 1949, over 3100 large, middle and small-sized reservoirs have been built in the basin. Economic growth has meant rapidly increasing water demand for agriculture, industry and domestic use (Cai and Rosegrant 2004). Climate change in the source area for the Yellow River has led to declining discharge, with data showing a declining trend for the past 50 years, especially since the 1990s (Chang et al. 2007). Tree planting and terracing activities for erosion control has also reduced runoff (Bardsley and Liu 2003; Sun et al. 2006). Climate change modelling predicts reduced summer rainfall, and drying in the Yellow River basin by 2045 (Nijssem et al. 2001). Therefore, assumptions about Yellow River water availability need to be reassessed in light of these hydrological changes (Giordano et al. 2004).

Sedimentation of the channel

A major issue with managing the lower Yellow River is excessive sedimentation of the channel that has elevated the river bed compared with the surrounding plain. This presents a serious flood risk, which in the past has been partly managed by increasing the height of dikes that run along the length of the lower Yellow River. Continuing to raise the dikes is not practical, so the problem is being managed in three ways: reducing sediment supply through catchment erosion control, trapping sediment in middle-basin dams, and scouring sediment from the lower Yellow River channel using WSDR events. In the 1990s, actual sediment loads were substantially below the levels in previous years. In 2000, the level was only five per cent of the 1956–1995 average (Giordano et al. 2004). This is partly because of reduced flow, but regardless of reduced sediment loads, there is a critical need to maintain sediment transport through the lower river.

Delta sediment balance

The essential character of the lower Yellow River delta, which contains a Ramsar-listed wetland area, is partly reliant on its rapid rate of seaward progradation, which gives rise to very active plant succession. The delta has received reduced sediment loads since the 1990s, which has caused the sedimentation rate to slow. In recent times, coastal erosion is thought to have exceeded sedimentation (Wang et al. 2004; Cui et al. 2009). In 1997, the sub-aerial tip of the abandoned delta receded 1.5 km; its mean annual recession rate was about 150 m in the following years (Fan and Huang 2005).

Reduction in extent and quality of riverine wetlands

The lower Yellow River has long been contained within major continuous dikes as a flood prevention measure. Over time, additional inner dikes have been constructed to allow settlement and agriculture within the diked land. This has seriously limited the extent of lateral surface water connectivity between the river and its floodplain. A few valuable riverine wetlands remain in the braided upper reach of the lower Yellow River, where the river still actively shifts its course. A study of wetlands along the lower Yellow River in Henan (Xiaolangdi to Dongbatou) found a reduction in riverine wetland area by 19 per cent between 1987 and 2002 (Liang and Ding 2004). While the total area of the rice wetland increased, the other types (beach, bulrush and pool) decreased. A study of wetlands in Kaifeng City by Cao (2008) found that between 1987 and 2002, the area of natural wetland reduced by about 45 per cent. Referring to the Henan Yellow River Wetland National Nature Reserve, Zhao et al. (2011) and Xu et al. (2011) reported that prior to 2000 and the operation of the Xiaolangdi Dam, every year the river overflowed and submerged all or a significant part of this area with seasonal floods. Regulation of the flow disrupted the wet–dry cycle, and typical wetland attributes have been lost. Much of the original wetland has been developed into farmland or fishponds for economic benefits.

Estuarine process alteration

Over the last five decades, reduced flooding in the delta area, associated with natural flow reduction and regulation by dams, has led to saltwater intrusion and increased soil salinisation (Qi and Luo 2007; Zhang and Zhao 2010). Seawater temperature has lowered during the fish-breeding season from April to June, and reduced nutrient levels and reduced primary productivity have contracted fish production and changed species composition (Fan and Huang 2008). Also, the reduction of flows has limited the ability of fish to return to the estuary after breeding (Fan and Huang 2008).

Water quality limiting river health

The Yellow River generally suffers from poor water quality (Giordano et al. 2004). For the basin as a whole, the percentage of the river length classified as Grade II has declined from 50.1 per cent in 1985 to 1.5 per cent in 2001. Over the same period, the percentage of the river length classified as worse than Grade V has increased from 3.7 per cent in 1985 to 25.4 per cent in 2001. The percentage of river length classified as Grade V or worse than V increased from 33.8 per cent in 1998 to 41.9 per cent in 2001. The major pollution indicators are petroleum materials; volatile phenol; ammonia nitrogen (main source being fertiliser and untreated sewage); chemical oxygen demand (COD); biochemical oxygen demand (BOD_5) (related to organic pollutants from wastewater); and heavy metals (Yu 2002; Giordano et al. 2004; Qi and Luo 2007).

3.2 Yellow River management policy framework

In response to concerns about the deteriorating natural environment of the Yellow River, and the declining quality of ecosystem services the river provided to society, Li (2004) formulated a policy framework for management of the Yellow River. The policy framework first announced by Li (2004) remains the fundamental guide to decision making for managing the Yellow River by the Yellow River Conservancy Commission (YRCC).

The framework has four levels:

- a vision statement
- four overarching objectives
- nine action strategies
- three approaches to understanding the river.

The vision statement for the Yellow River, or the 'ultimate target', is:

- 'Keeping the Yellow River Healthy'.

The vision encompasses both ecological health and social-economic health, which can be expressed as the total amount of water resources, flood discharging capacity, sediment-carrying capacity, self-purification capacity, and the capacity to maintain ecosystems (Li 2004).

The four overarching objectives (or criteria) expressed as negatives, or the outcomes that are *undesirable* are known as 'the four nos':

1. no embankment breaching
2. no river running dry
3. no water pollution beyond standard
4. no river bed rising further.

The nine actions strategies were devised to target the main identified problems: less water, more sediment, an imbalance of water and sediment conditions, and benign development of river ecosystems. The nine action strategies are (Li, 2004):

1. Take measures to reduce sediment inflow to the Yellow River.
2. Manage water resources utilisation of the Yellow River basin and its related regions effectively.
3. Strengthen the study on water transfer plans to increase the water resources of the Yellow River.
4. Establish a WSDR system.
5. Work out a scientific, and reasonable, general plan for controlling and managing the lower river course.
6. Create favourable hydrological processes to mitigate the shrinking of the main channel.
7. Meet water demands to maintain river's natural cleaning capacity.
8. Manage the Yellow River Delta to reduce seawater impact to the lower reach.
9. Maintain the ecological system sustainable in the Yellow River Delta.

To implement the actions, the river is considered in three ways:

1. the 'physical' Yellow River or the actual river actions are applied to
2. the 'digital' Yellow River or the numerical simulation model of the natural, social and economic aspects of the river
3. the 'scaled' Yellow River or the physical models of the river used to simulate and experiment with particular natural phenomena or proposed actions.

Liu et al. (2006) further developed Li's (2004) vision and policy of 'Keeping the Yellow River Healthy by presenting a list of 'Healthy Indicators of the Yellow River' that were aligned with Li's (2004) four criteria ('the four nos'). The five indicator categories were:

- flow continuity
- channel configuration for water and sediment transportation
- water quality standard
- river ecosystem
- water supply capacity.

This list explicitly includes river ecosystems. In Li's (2004) policy framework, ecosystem health was only an implicit target, with the exception of action 9, which was specific to the delta only. Including water supply capacity (i.e. capacity to supply both human and environmental water demands) as an indicator of a healthy river is an acknowledgement that ecological health and social health are inextricably linked, especially in a river like the lower Yellow River where the water resource is relatively scarce. Liu et al.'s (2006) indicator categories, together with Li's (2004) policy framework were used in this project as a set of basic principles from which to develop environmental flow objectives and recommendations for the lower Yellow River.

3.3 Objective-setting process for environmental flows

The environmental flow objective-setting process was based around meeting the flow needs of the defined assets. The major assets are certain wetlands and the river channel, but within these units are assets identifiable at a finer scale. These assets, such as certain species or communities, or physical and chemical processes, provide the wetland and river channel assets with their intrinsic conservation values, and their value in providing ecosystem services to society. These fine-scale assets can be evaluated with a framework that divides the ecosystem and its processes into the following linked categories:

- geomorphology
- hydrology
- water quality
- waterbirds
- fish
- macroinvertebrates
- plants.

The environmental flows framework requires experts from the disciplines associated with these categories to make individual contributions about issues and the objectives. These inputs are then merged to create a minimum set of objectives that jointly meet all of the requirements.

The objectives are derived from a conceptual understanding of flow-ecology, flow-geomorphology, and flow-water quality relationships. Some of these relationships are concerned with the lifecycle of biota, and others are concerned with specific hydraulic habitat requirements, or specific process requirements. Ultimately, the objectives are expressed as flow magnitudes, with associated specifications of frequency, timing, duration and rate of rise and fall. The values of frequency, timing, duration and rate of rise and fall are derived from ecological knowledge or characterisation of the natural flow regime. The magnitude value is derived from hydraulic relationships that relate discharge with water depth, velocity and bed shear stress. The hydraulic relationships are derived from hydraulic modelling of the river.

Chapter 4. Previous Environmental Flows Assessment Work

4.1 Legislative and institutional arrangements

The practice of water allocation in the Yellow River Basin is based on the *1987 Yellow River Water Allocation Scheme*, established and issued by the State Council of China in 1987, which sets a cap on abstraction at 37 × 10^9 m^3 per year and a quota for each province. This volume is based on an average runoff year of 58 × 10^9 m^3 (Shao et al. 2009). The remaining water comprises 20–21 × 10^9 m^3 reserved for environmental purposes.

In 1997, the Yellow River suffered its most severe dry conditions on record. In response, a *Plan of Annual Available Water Supply Distribution and Water Volume Regulation of the Main Stream of the Yellow River and Terms of Water Volume Regulation and Management* was implemented in December 1998 with approval of the State Council; China State Development and Planning Commission (CSDPC); and the Ministry of Water Resources. Under this plan, the YRCC issues operation plans for allocating available water in the main stream according to the Yellow River Water Allocation Scheme. In years when annual runoff is less than the average of 58 × 10^9 m^3, the quota of 37 × 10^9 m^3 available for utilisation is reduced proportionately (Sun and Dong 2009). This practice, known as unified water regulation, which began in 1999, coincided with the commencement of operation of Xiaolangdi Dam, when much greater control over water and sediment was possible (Li 2004; Zhu 2006).

On 24 July 2006, Premier Wen Jiabao subscribed Decree No.472, promulgating *Regulations of Yellow River Water Regulating*, an ordinance that was put into effect on 1 August 2006 (Li 2006; YRCC 2006). The Regulations were constituted '…*in accordance with Water Law of the People's Republic of China, to enhance integrated Yellow River management, realize sustainable use of Yellow River water resources, and promote social and economic development and the improvement of ecological environment in the Yellow River Basin and relevant regions*' (Li, 2006, also see Article 1 of the Regulations (YRCC 2006)).

Article 3 of the Regulations of Yellow River Water Regulating includes the requirement that, '*While the domestic water use in rural and urban areas is the highest priority of water supply, Yellow River water regulating shall also balance the water demand of agriculture, industry and environment so as to prevent the Yellow River from discontinuous flowing*' (Li 2006; YRCC 2006). The regulating comprises yearly water allocation planning, developing a monthly regulating scheme, developing a ten-day regulating scheme and real time regulating instructions. The regulating year begins 1 July and ends 30 June the following year (Article 10, YRCC 2006). The yearly allocation plan is based on forecast annual runoff and reservoir storage (Article 13, YRCC 2006). The 10-day plans are required in cases of high water demand (Article 14, YRCC 2006). In severe drought, in a low-flow emergency at a provincial boundary or key sites, a failure of reservoir operation, or a significant water pollution event, the YRCC will be responsible for the emergency water regulating (Article 21, YRCC 2006). This may require direct regulation of intakes by YRCC, or adjustment of water plans by water management authorities (Article 24, YRCC 2006), daily reports by water management authorities (Article 25, YRCC 2006) or other direct action (Article 26, YRCC 2006).

In the lower Yellow River, water allocation for domestic, industrial and agricultural use is coordinated with sediment management and environmental flow management as a component of integrated Yellow River basin management (Sun and Dong 2009). To support the allocation process, a number of guidelines have been established for environmental flows.

4.2 Current environmental flow practice for the lower Yellow River

4.2.1 Basic flow allocation guidelines

Environmental flows are implemented on the lower Yellow River each year in coordination with forecast supply, anticipated demands and known reservoir storage. There are no guidelines documented in English that explain in detail how the allocation is made. However, Ni and Qian (2002) made reference to a report published in 2000 by YRCC titled *Major Problems of the Yellow River and Their Countermeasures*, where it was claimed that:

- the minimum flow rate should be 50 m^3/s
- the total volume in the non-flood season (7-month period, Nov–May) at Lijin should be 5 × 10^9 m^3 to maintain delta wetlands, and to supply an average discharge of 240 m^3/s to the sea
- the total volume of flow in the flood season (5-month period, June–Oct) at Lijin is 15 × 10^9 m^3 to maintain channel capacity
- for flow self-purification and other functions the requirement is the same as the water demand for sediment transport in the flood season and ecological protection in the non-flood season.

According to Cai and Rosegrant (2004), citing Hong Shangchi (YRCC, personal communication, 2002), the value of 5×10^9 m^3 for non-flood season flow at Lijin was based on the observation that the delta ecosystems were basically sustained under similar flow conditions during the 11-year successive droughts from 1922 to 1932. However, this flow volume has also been justified on other grounds. For example, Shi and Wang (2002) estimated that the environmental flow requirement of the Lower Yellow River at Lijin for the non-flood season was $5 – 6 \times 10^9$ m^3. This estimate was based on the objective of assimilation and dilution of seven major pollutants.

For some time, it has commonly been understood that the annual environmental water requirement for the Yellow River is $20–21 \times 10^9$ m^3 (e.g. Xu et al. 2002; Giordano et al. 2004; Cai and Rosegrant, 2004). The estimate of 15×10^9 m^3 for sediment flushing was based on a perceived need to annually flush 0.4×10^9 tonnes of sediment at an assumed rate of 35 kg/m^3 (see Giordano et al. 2004). Before this, in 2002, a lower estimate of $8 – 12 \times 10^9$ m^3 flow requirement for sediment transport in the flood season was made by Shi and Wang (2002).

The data published by Wang et al. (2010) shows that the reality of sediment transport in the lower Yellow River has been somewhat different to what was anticipated. For the WSDR events from 2002 to 2006, which ranged from 13 to 29 days duration, the event mean sediment concentration exceeded 35 kg/m^3 only in 2003 (when it was 40 kg/m^3); in the other four years it ranged from 12 to 18 kg/m^3. The total volume of water used to flush sediment in each WSDR event ranged from 2.4 to 5.3×10^9 m^3, which represents only 16 to 35 per cent of the intended annual allocated volume. The total sediment load flushed by each of these events ranged from 51 to 108×10^6 tonnes, which represents only 13 to 27 per cent of the load that was expected to be transported. So, in hindsight, the original estimate of 15×10^9 m^3 for sediment flushing seems generous. This volume appears to have been intended to meet flow requirements for the entire high flow season from June to October, not just the WSDR event itself.

A volume of 1×10^9 m^3 is included in the environmental allocation, according to Cai and Rosegrant (2004), to account for loss in river flow due to the effects of soil conservation measures (based on the estimate for 1997 by Zhu and Zhang (1999)). According to Ni and Qian (2002) the volume is to account for water loss due to evaporation and leakage along the river. Either way, the allocation comprises an amount of 1×10^9 m^3, which provides no benefit to the in-stream or floodplain environments. If anything, the allocation is a disbenefit. Any incidental environmental benefits to the lower Yellow River of providing the WSDR component and the minimum flow component at Lijin (such as improved water quality, provision of in-stream habitat, or groundwater recharge) are implicit only. Also, the calculation does not explicitly consider the environmental flow benefits of the regime, or any additional environmental requirements that might be needed, in the middle and upper Yellow River. The broad guidelines discussed above are inadequate as rules to assist with daily flow management.

These guidelines are inadequate as rules to assist with daily flow management. Although not a formal set of rules, Liu Xiaoyan's *Healthy Yellow River's Essence and Indicators* (Liu et al. 2006) sets out a rationale for environmental flows and tabulated a range of guidelines to meet various objectives. These guidelines are summarised here, but the extent YRCC considers them when making routine flow management decisions in the lower Yellow River is unclear. However, Liu and Liu (2009) noted that, with respect to environmental flow recommendations, '…*the suggestions have been applied in practice partly by the Yellow River Conservancy Commission*'.

Liu et al.'s (2008) *Environmental flows of the Yellow River* produced a set of recommendations for daily flow management that were different to those in Liu et al. (2006). This work is summarised in a later section of this report on holistic studies.

Recently, the YRCC revised the estimate of the annual environmental water requirement for the Yellow River (Dr Jiang Xiaohui, Yellow River Institute for Hydraulic Research, YRCC, pers. comm. November 2010). It is now considered that for sediment transport, delta wetlands, and flow through the estuary to the sea, an annual allocation of 13.5×10^9 m^3 would be adequate to survive a drought year, while 18.5×10^9 m^3 would maintain satisfactory river health. The desirable minimum flow at Lijin is 150 m^3/s. Of the minimum flow, a proportion is used by Shengli Oilfield, and the remainder flows to the Bohai.

Only a small percentage of the annual water allocation is used directly by the wetlands of the delta. Restoration activities involving artificially delivering freshwater to the wetlands began in July 2002. The delivery of water was governed by the Dawenliu Management Station, in the Yellow River Delta Nature Reserve (Li et al. 2011). Since 2002, about 2.8 Ï 10^6 m^3 of freshwater has been directed from the river annually through an artificial channel to an area located ~4 km south of the current river channel and ~15 km west of the estuary (Cui et al. 2009). Consequently, hydrological conditions, salinity, and vegetation communities have been restored to that area (Li et al. 2011). Flow to the delta wetlands is via gravity fed supply channels, but the regulator does not become operational until the river flow exceeds 3000 m^3/s (Dr Jiang Xiaohui, Yellow River Institute for Hydraulic Research, YRCC, pers. comm., November 2010). The hydrology of the outermost part of the delta near the river channel is not regulated, being influenced by tides and floods. Some freshwater would be used by wetlands in this part of the delta for environmental benefit, but the volume of water has not been estimated.

4.2.2 Absolute lowest flows

Article 26 of the Regulations of Yellow River Water Regulating states that, '*The warning standards of low flow emergency at provincial boundary or key sites shall be defined by the Yellow River Conservancy Commission*' (Li, 2006). This requirement is intended to avoid cease to flow conditions in the river. In 2003, the YRCC developed the policy, *Yellow River Water Regulation Emergency Management Guideline* to provide a warning flow for critical gauges along the lower Yellow River (Table 1). The warning flow guideline was established to meet the fundamental principle of avoiding cease to flow conditions at any location (e.g. see Tian and Wang, 1997) rather than as a measure to meet specific environmental needs. However, there was recognition within YRCC that drying of the river had negative consequences for river health.

Table 1. Warning flow thresholds for gauges on the lower Yellow River.

	Huayuankou	Gaocun	Sunkou	Luokou	Lijin
Warning flow	150 m^3/s	120 m^3/s	100 m^3/s	80 m^3/s	30 m^3/s

Source: YRCC.

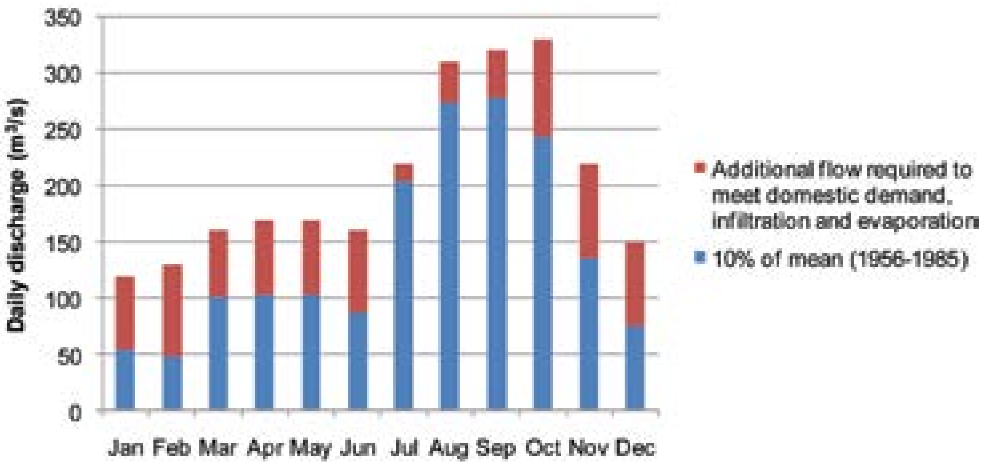
Liu et al. (2006) used the Tennant method[7] to estimate the monthly minimum flow required to maintain continuity of the flow and provide a minimum flow for environmental protection. The minimum flow for each month was calculated as a percentage of the historical mean monthly discharge in the benchmark time series, which was taken to be 1956–1985. The calculation was based on 10 per cent of the mean monthly flow. Taking estimates of the domestic water demand and losses from infiltration and evaporation into consideration, the minimum flow that would supply domestic demands and prevent cease to flow was calculated for each month (Table 2 and Figure 5). These estimates are higher than those for the warning flow (Table 1), because the warning flow signals a potential emergency situation, while the minimum flow of Liu et al. (2006) (Table 2) provides for domestic water demand and also delivers a low level ecological benefit.

Table 2. Monthly flows to meet domestic demands and prevent cease to flow at key lower Yellow River cross-sections.

Gauge	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s
Xiaolangdi	110	110	160	160	180	160	190	290	280	310	200	150
Huayuankou	120	130	160	170	170	160	220	310	320	330	220	150
Lijin	50	60	70	70	70	60	170	260	260	240	140	70

Source: Liu et al. (2006).

Figure 5. Estimated environmental flows to provide domestic demands, prevent cease to flow, and provide minimum ecological requirements on the Yellow River at Huayuankou.



Source: Liu et al. (2006)

7 see section 4.3.3 for discussion of the Tenant method

4.2.3 Minimum monthly flows to maintain ecological health

Liu et al. (2006) used the Tennant method to estimate the monthly minimum environmental flow requirements of the Yellow River for aquatic ecosystem protection (Table 3). The minimum flow for each month was calculated as a percentage of the historical mean monthly discharge in the benchmark time series, which was taken to be 1956–1985. The calculation was based on 20 per cent of the mean monthly flow, and in reaches with certain high value ecological assets, including the lower Yellow River, the values for April, May and June (spring) were based on 40 per cent of mean monthly discharge (Liu, 2006).

Liu et al. (2006) implied that the monthly flows required for ecosystem health, calculated by their method, were the same as historical flow levels in the 1980s. Liu et al. (2006) also suggested that by implementing this flow regime it would be possible to restore the aquatic ecosystem of the Yellow River to the level of the 1980s. The problem with this argument is that, at Huayuankou, the monthly mean flows in the 1980s were actually similar to flows in the benchmark 1956–1985 period selected by Liu et al. (2006).

Table 3. Monthly flows to meet requirements for ecosystem protection at key lower Yellow River cross-sections.

Gauge	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s
Xiaolangdi	100	100	200	400	390	340	360	490	500	430	240	140
Huayuankou	110	100	200	410	410	340	410	550	550	490	280	150
Lijin	100	100	150	300	280	250	340	510	530	490	280	150

Source: Liu et al. (2006).

4.2.4 Flow to maintain water quality

In China, the most common method of determining the flow required for self-purification or receiving pollutants (meaning assimilation and dilution) is to calculate the mean of the lowest monthly flow totals for each year over the last 10 years of record[8] (Zhang et al. 2006).

Using the concentration limits of the required water quality grade, it is possible to estimate how much additional flow, if any, is required to achieve that concentration. The estimate has to take into account the concentration of pollutants (usually COD and NH_3-N are the parameters of concern) in the water were it enters the reach. Where the water already meets the required standard, the same calculation method can be used to set the limits of pollution discharged to a reach in order to remain within the required water quality grade. In the lower Yellow River the target is Grade III (Drinking water 2nd Class (treatment required)); sanctuaries for common aquatic species; fish survival in winter; fish migration; aquaculture; contact recreation). Differences in the estimate of the required flow might arise from differences in the way the method was applied. For example, differences will arise depending on the period of hydrological record that was used, which values of reach inflow pollution concentrations were selected, and which pollution parameters were used.

Liu et al. (2006) used the work of Hao et al. (2005) to recommend the discharge required for self-purification of reaches of the Yellow River. The estimate was based on COD and NH_3-N, and it was assumed that the sewage into the main watercourse of the Yellow River met national standards. The estimated minimum flow to achieve water quality standards for the non-flood period (November to June) was 260 m^3/s at Xiaolangdi, 290 m^3/s at Huayuankou (Hao et al. 2005) and 60 m^3/s at Lijin (Liu et al. 2006).

4.2.5 Flow to transport sediment and maintain channel capacity

Liu et al. (2006) and Liu and Liu (2009) reported the results of various research efforts concerning sediment transport in the lower Yellow River. Based on the observed data series of 168 floods from 1974 to 1990, Yue (1996) proposed that the most efficient discharge and sediment concentration was 3500 m^3/s and 75 kg/m^3 respectively. This finding agreed with the observation that the velocity at Gaocun did not appreciably increase beyond around 3000 m^3/s (Liu et al. 2006). Other observations of scouring capacity found that there was no increase beyond around 3500 m^3/s (Liu et al. 2006). These flow levels were close to bankfull capacity of the channel at the time. Liu et al. (2006) and Liu and Liu (2009) set the objective for bankfull capacity at 4,000 m^3/s (as a minimum), and because of the observed relationship between sediment transport efficiency and bankfull discharge, set this as the target discharge for an annual sediment flushing flow (WSDR) for the lower Yellow River.

8 In other countries, a common flow statistic used for setting licences for pollution discharges, or for defining low flows in general, is the 7Q10, or the lowest stream flow for seven consecutive days that would be expected to occur once in ten years (Smakhtin 2001). The Chinese equivalent is not 30Q10 because: (i) the statistic is not based on any 30 consecutive days, but flows within (arbitrary) calendar month periods (ii) the statistic is the mean of the lowest monthly flow in each of the 10 consecutive years, not the lowest monthly flow over a 10 year period and (iii) normally the previous 10 years of record are used, not the long term record, or records from the unregulated flow period.

4.2.6 Multi-objective environmental flow regime

Liu et al. (2006) combined the estimated requirements for minimum flow, ecosystem protection, self-purification, and sediment transport and channel maintenance to derive a flow regime that would meet all of these objectives (Table 4). It is not clear how Liu et al. (2006) derived the monthly values for the combined recommended flow regime. The flows in most months were set by the water purification requirements, and July had a sediment transport event, but the other values were only loosely related to the minimum flows and ecosystem protection flows. It is worth noting that not long after these recommendations were published, the same author presented two significantly different sets of multi-objective flow recommendations in Liu (2007) and Liu et al. (2008).

Table 4. Monthly flows to meet multiple objectives at key lower Yellow River cross-sections.

Gauge	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s
Xiaolangdi	260	260	260	>260	>260	>260	>260/4000	>300	>300	>300	260	260
Huayuankou	290	290	290	>290	>290	>290	>290/4000	>330	>330	>330	290	290
Lijin	100	100	100	300	280	250	340/4000	500	500	240	140	100

Source: Liu et al. (2006).

4.2.7 Recent historical flow regime

The implementation of minimum baseflows began in 2000 and WSDR began in 2002 following observations of negative social, economic and environmental impacts of the flow regime, especially cease to flow events during the 1990s (Tian and Wang 1997; Jiao et al. 1998; Cui 2002; Liu and Zhang 2002; Xia et al. 2004)[9], and with the completion of the Xiaolangdi Dam in late 1999, which allowed greater control of water resources. The WSDR event was first tested from 4–15 July 2002 with coordinated operation of Xiaolangdi and Sanmenxia Reservoirs (Xu and Si, 2009). Annual WSDR events have been implemented since that time, with different conditions applying each time (Xu and Si, 2009).

The implementation of controlled minimum baseflows appears to have begun in 2000, adhering to the 50 m^3/s minimum flow rule at Lijin (Figure 6) that was mentioned by Cai and Rosegrant (2004) and Giordano et al. (2004). Also, flows at the other gauging stations were maintained above the warning flow thresholds (Table 1). The 50 m^3/s minimum flow at Lijin appears to have been applied until 2003, after which baseflows at all stations along the river were increased. In the non-flood season, flows at Lijin were usually 100–200 m^3/s (Figure 6). In the flood season, the baseflows were higher, but more variable from year to year. After 2003, the flows at all stations met the monthly minimum flows recommended by Liu et al. (2006) for providing for domestic water demand and also delivering a low-level ecological benefit (Table 2, Figure 6). Most of the time, flows met the monthly minimum flows recommended by Liu et al. (2006) for maintaining ecosystem health (as defined by an arbitrary method of factoring monthly flows), and for meeting the self-purification target of achieving Grade III water quality (290 m^3/s at Huayuankou and 60 m^3/s at Lijin) (Figure 6).

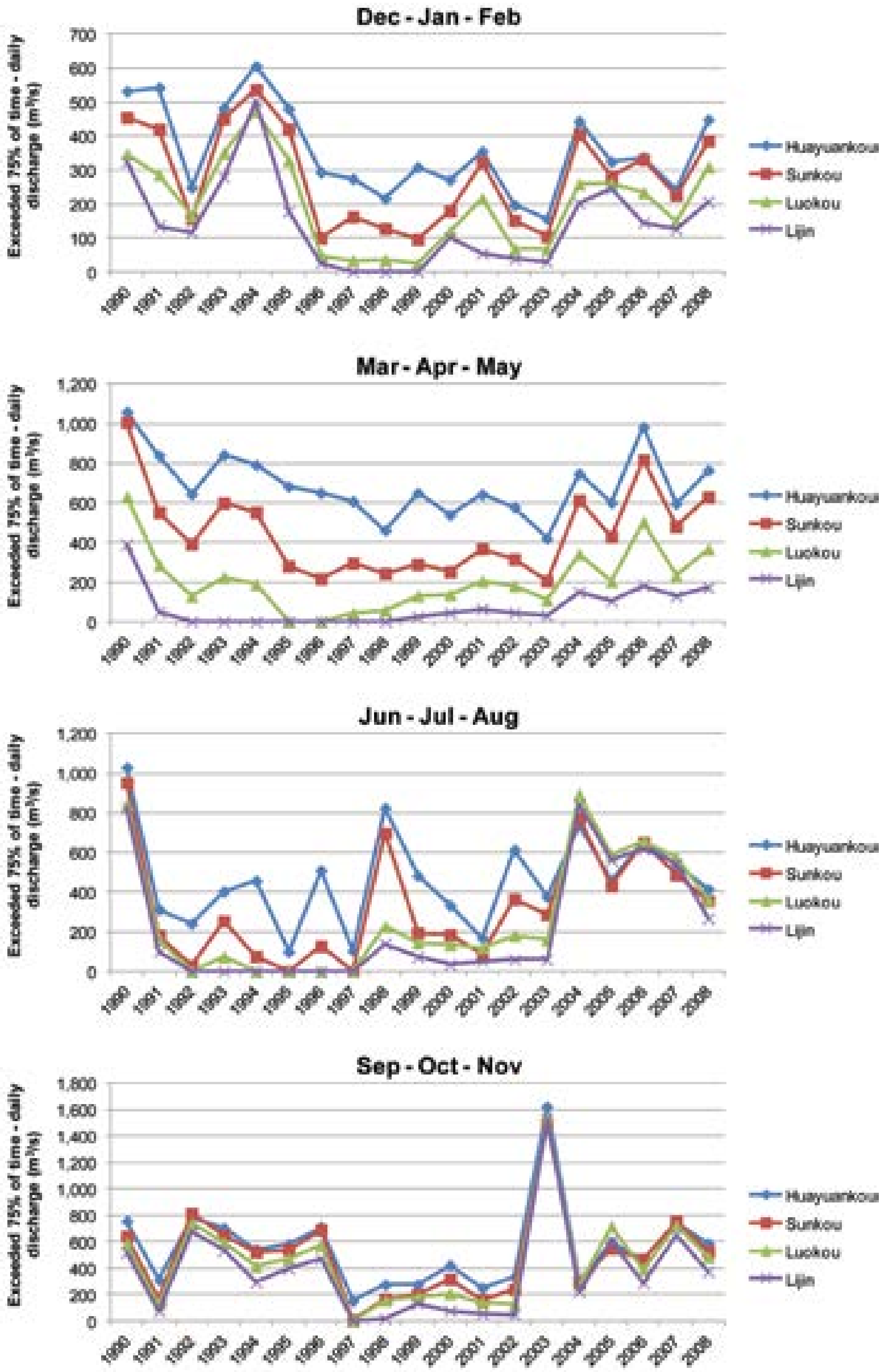
The WSDR flow varied in magnitude and duration, with the magnitude increasing each year until 2006, when flows of >3,500 m^3/s were delivered (Figure 7). This is in agreement with the target set by Liu et al. (2006).

Since 2000, the annual flows at Lijin have varied from 3.5×10^9 m^3 (in 2000) to 23.4×10^9 m^3 (in 2004) (Figure **8**). The annual totals were low from 2000 to 2003 mainly because baseflows were close to the minimum limit over that period. The first WSDR was implemented in 2002, but its duration was relatively short (15 days) and the non-flood period flows were lower than in previous years, so the annual total did not increase. In 2003, the WSDR was of a similar total volume to that of 2002, but the flow volume during the flood season was much higher so annual flows were higher; the 2003 non-flood season baseflows remained at minimum levels. From 2004 to 2008, the annual flow totals ranged from 14.9×10^9 m^3 to 23.4×10^9 m^3. This range covers the flows recommended in recent years by YRCC as adequate ($13.5–18.5 \times 10^9$ m^3). The flood season flows only reached the previous target of 15×10^9 m^3 in 2007. The non-flood season flows ranged from 2.9×10^9 m^3 to 9.2×10^9 m^3, which can be compared with the previous target of 5×10^9 m^3.

9 During the periods of cease to flow, water was not available to industry, and various enterprises and oilfields had to suspend production. At the time, it was estimated that the loss amounted to 40 billion RMB (Liu and Zhang 2002) or US$10 billion since 1990 (Xu 2001). Losses of 200 million RMB per year were sustained during the 1970s and 1980s, with losses rising to 4 billion RMB per year in the 1990s (Liu and Zhang 2002). In the 1990s, losses in cereal production amounted to 1.3 million tonnes or an economic loss of 1.6 billion Yuan. During the cease to flow period, there was a maximum annual agricultural production loss of more than 3 billion Yuan (Liu and Zhang 2002). In 1995, the domestic water supply was insufficient in Dongyin, Binzhou and Dezhou city regions, with more than 100,000 residents not having adequate supplies. Residents had to join long queues and carted water from appointed public water taps every day (Liu and Zhang 2002).

The flow records indicate that from 2000, the year after the Xiaolangdi Dam came into operation, the regulated flow has generally aligned with the flow regime recommended by Liu et al. (2006). Since 2004, the total flows have been within the target range most recently set by YRCC.

Figure 6. Annual statistic (flow exceeded 75% of the time) to represent baseflows for 3-month long seasons, from 1990 to 2008 for the lower Yellow River.



Note: variable y-axis scale.

Figure 7. Annual statistic (flow exceeded 5% of the time) to represent high flows for the period June to September (the water-sediment discharge regulation period from 2002), from 1990 to 2008 for the lower Yellow River.

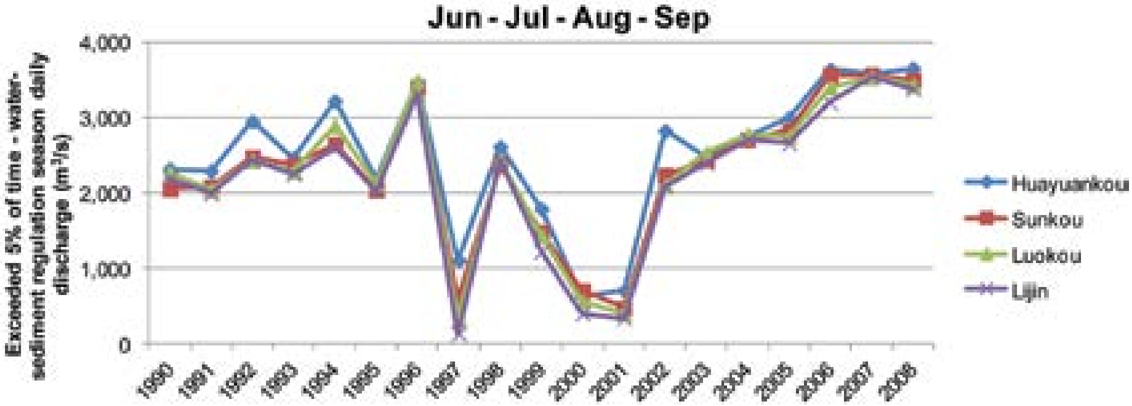
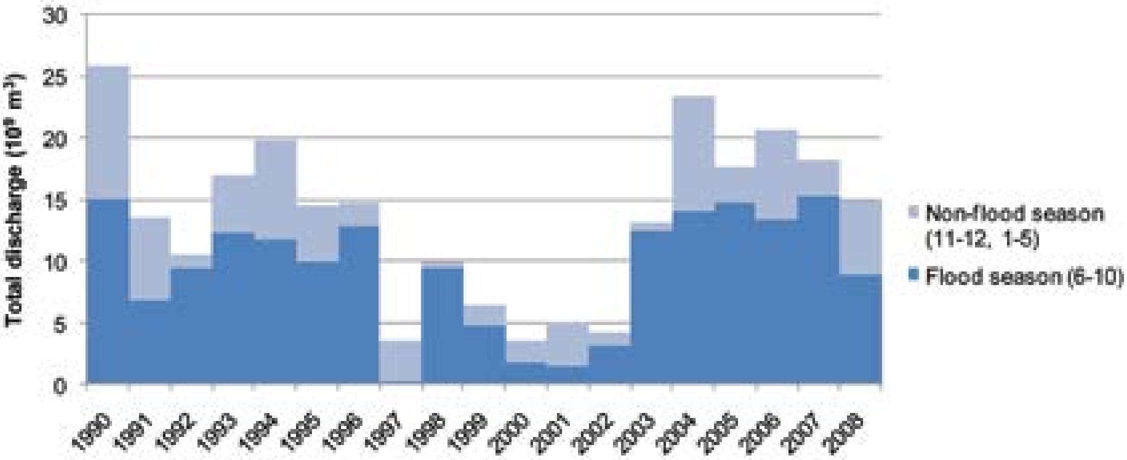


Figure 8. Annual flows at Lijin, split by flood and non-flood seasons, as defined by YRCC.



4.3 Other research on environmental flow requirements for the lower Yellow River

Previous research on environmental flow needs of the lower Yellow River can be grouped into four main categories:

- basin-scale research
- single-asset focused research
- hydrology research
- holistic research.

4.3.1 Basin-scale research

Basin-scale approaches to environmental flow assessment are undertaken as a component of basin-wide water balance studies. Examples of these studies in the Yellow River basin are Yang et al. (2007); Yang et al. (2009b); and Zhang et al. (2006).

Basin-scale studies are important for planning water allocation at the basin-scale and long-term scale. They tend to use either existing estimates for the water needs of ecological assets, or broad-scale estimates. These studies tend not to consider water use options to achieve different levels of river health, i.e. only a single estimate of environmental water needs is provided. Also, the focus is on estimating total water use, rather than specification of environmental flow requirements at the scale of individual assets and over-time scales relevant to routine river management decision making. Management decision making is the main focus of this study, so catchment-scale studies are not considered here any further.

4.3.2 Single-asset focused research

Yellow River Delta

The Yellow River delta area has received a lot of attention in environmental flow research, largely explained by its high conservation values. Cui et al. (2009) proposed a set of management objectives for the Delta National Nature Reserve with the aim of preserving the ecological characteristics of the Ramsar-listed wetland. By undertaking a correlation analysis between aspects of the wetland biota and the water regime, the ecological water requirement for the wetlands was determined according to three classes – minimum, moderate and perfect – corresponding to the basic, moderate and perfect management objective, respectively. The management objectives were:

- maintain the newly created wetlands and waterfowl (basic)
- recover and protect the damaged wetlands (moderate)
- maintain functions and procession of the whole wetland ecosystem (perfect).

The results showed that the minimum, moderate and perfect water requirements were 3.8×10^9 m^3, 4.9×10^9 m^3 and 6.5×10^9 m^3 per year respectively. These estimates are exclusive of the standard estimate of 15×10^9 m^3 per year for sediment flushing, which was also considered an important flow component. The ecological water requirements for different wetlands were calculated in normal flow periods (November–March), special fish breeding periods (April–June) and flooding periods (July–October).

Cui et al. (2010a) applied a method for calculating wetland environmental water requirements based on the response of habitats to water level, and determined the critical water level through assessment of the functional integrity of habitats. The functional integrity represents the intactness of environmental, ecological and productive functions – water-salt balance, habitats for rare waterfowls, biodiversity maintenance, raw materials (*Phragmites australis* yield), and recreation. When the functional integrity index is below 0.5, wetland ecosystem is considered to be in poor quality and wetland functions are poorly performed; when the index is between 0.5 and 0.7, wetland ecosystem is in medium quality while wetland functions are performed at an average level; and when the index is higher than 0.7, wetland ecosystem is in good quality while wetland functions are perfectively performed.

The results of Cui et al. (2010a) showed that water levels between 5.0 m and 5.5 m were required to maintain the functional integrity of the delta wetlands at a value higher than 0.7. One of the dominant plants in the delta, *Phragmites australis*, tolerates water level fluctuation of about ± 0.25 m without a change in wetland functional integrity. The minimum, optimum and maximum environmental water requirements for the delta were 9.42×10^6 m^3, 15.56×10^6 m^3 and 24.12×10^6 m^3 with water levels of 5.0 m, 5.2 m and 5.5 m, corresponding to functional integrity indices of 0.70, 0.84 and 0.72, respectively.

In a study of the flow needs of the delta wetlands, Sun et al. (2008) considered temporal variability of flow input and output and the amount of water needed for both consumptive and non-consumptive uses. The rule of summation was used to calculate consumptive water requirements and the rule of compatibility was adapted to estimate the non-consumptive ones. It was determined that the minimum, medium and high levels of annual environmental flows were 13.4×10^9, 16.3×10^9 and 27.5×10^9 m^3, respectively, which represented 23.7 per cent, 28.7 per cent and 48.5 per cent of the natural river discharge. Water requirements differed across months. The months of May to June, August and October were identified as the most critical periods for maintaining the environmental flows. The basic purpose of water entering the system was to compensate for water losses due to evaporation, and to maintain an acceptable level of salinity in the estuary.

The highest water need was for salinity management (Sun et al. 2008). Under minimum and medium levels of environmental flows, salinity requirements were sufficiently high to also account for sediment transport needs. The lowest water requirement came from freshwater wetland maintenance, which was not greater than two per cent of total flow needs. Thus, Sun et al. (2008) concluded that direct biological needs were secondary to the objectives of maintaining the salinity balance and sediment transport within the estuary.

In 2005–2007 the Sino–Dutch Study Program YRD-EFS investigated the environmental flow needs of 23,000 ha of Yellow River Delta wetlands (Lian et al. 2007; Lian et al. 2008; Deltares 2009). One key product from the project was a decision support tool that allowed water volume to be balanced against environmental outcomes. The project adopted a landscape ecology approach and used remote sensing, GIS, knowledge of wetland plant physiology, ecology and hydrology to couple the mechanisms between water regime and ecological process (Wang and Lian, 2010). The decision support model was used to evaluate the ecological response in wetlands to different water supply scenarios. The results showed that the wetlands have potential to be habitat for rare birds, but at the time of the study the habitat was not considered to be in good condition. It was estimated that an annual allocation of 0.35×10^9 m^3 of water would rehabilitate the delta wetland ecosystem.

Sediment transport

Maintaining sediment transport and channel capacity are two of the biggest management issues of the lower Yellow River because of their implications for flood risk. Therefore, this topic has been the focus of much research over the years (see Liu et al. 2006). It is fair to say that the sediment transport function of the Yellow River has traditionally not been viewed as part of an environmental flow regime as it was perceived to provide utilitarian rather than ecological benefits. However, the shape of the channel has a major influence on the availability of suitable hydraulic habitat for biota, and the mobilisation of bed sediments and the generation of spates of highly turbid water at a certain time of the year have a critical effect on biota, so it is important to incorporate the sediment transport objectives into holistic environmental flows assessments.

Water quality

Successful management of water quality is ultimately achieved by addressing the source of pollutants. However, as an interim measure it may be considered prudent to ameliorate water of poor quality by mixing it with water of better quality. In China, rivers are considered to have a capacity for self-purification. In other words, the river can process a certain load of pollutants. Liu et al. (2006) cited the work of Hao et al. (2005) who estimated the flows required to achieve acceptable self-purification capacity were 290 m^3/s at Huayuankou and 60 m^3/s at Lijin, but others have also made estimates.

Using the period 1977–2006, Liu et al. (2008) calculated the flow suitable for achieving Grade III COD levels assuming lowest 10-year monthly discharge. The values were 300 m^3/s at Xiaolangdi and 320 m^3/s at Huayuankou. Ni and Qian (2002) used the method of the 10-year lowest monthly flow (prior to the drying phase of the 1990s) to estimate the flow required to achieve Grade III in the lower Yellow River. The values were 231.5 m^3/s for Sanmenxia-Huayuankou, 234.3 m^3/s for Huayuankou-Gaocun, 146.0 m^3/s for Gaocun-Aishan and 18.1 m^3/s for Aishan-Lijin.

Estuarine phytoplankton

At the time the Xiaolangdi Reservoir was designed, some held the view that '…*By using reservoir* [i.e. Xiaolangdi] *storage effectively, the large runoff now being lost to the sea during the flood season will become available for irrigation and other beneficial uses*' (Ludwig et al. 1995). However, rather than being totally 'lost to the sea', water entering the estuary and the sea plays a vital role in maintaining ecological productivity.

On the basis of its role in primary productivity, Zhao R et al. (2010) selected the phytoplankton community as a bio-indicator to represent the various ecosystem components influenced by hydrological and hydrodynamic processes in the Yellow River estuary. Based on regression analysis, a response model was established for describing the relationship between characteristics of phytoplankton communities (chlorophyll a, Fucoxanthin, chlorophyll b, and pyridinin) and salinity, COD, ammonia nitrogen, and dissolved oxygen. An eco-hydrodynamic model, combining a phytoplankton growth model with a hydrodynamic model, was developed to simulate relationship between river discharge and preference of phytoplankton in the estuary (Zhao R et al. 2010).

Threshold values of environmental flows in the estuary were determined on the basis of achieving objectives at a high, middle and low level. This translated to maximum, medium, and minimum annual environmental flow requirements that represented 105–111 per cent, 65–68 per cent and 31.7–32.4 per cent of natural runoff (Zhao R et al. 2010). The maximum, medium and minimum annual environmental flows of critical habitats were estimated to be 45–48 × 10^9 m^3, 28–29 × 10^9 m^3, and 13.6–13.9 × 10^9 m^3 respectively. It was determined that, historically, the river discharge would have met the requirements of the minimum environmental flows, except during April. However, the flows did not satisfy the medium and maximum water requirements of habitats (Zhao R et al. 2010).

Estuarine salinity for the spawning habitat of Chinese shrimp

Sun and Yang (2010) selected Chinese shrimp (*Penaeus chinensis*) as a critical bio-indicator for ecosystem health in the Yellow River estuary. The environmental flow objectives were set in terms of target salinities and river discharge for spawning habitat. They used a hydrodynamic model to establish a relationship between salinity and freshwater inflows. Based on knowledge of the salinity and depth requirements, Sun and Yang (2010) were able to model the time series of spawning habitat availability as a function of monthly discharge, according to three levels of ecological objectives (high, medium and minimum).

Fish

Jiang et al. (2010) followed a building block approach similar to Tharme and King (1998), Arthington (1998), SKM et al. (2002), WET (2007) and Gippel et al. (2009a) to assess the flow needs of fish in the lower Yellow River. Fish were selected as the best bio-indicator of the general health of the ecosystem. The basic steps were to first define the assets, which in this case were limited to three fish species (*C.(Cyp) carpio* (Yellow River carp), *Coilia ectenes* (estuarine tapertail anchovy) and *Anguilla japonica* (Japanese eel)). Then, flow-ecology relationships were used together with information provided by a 1-D hydraulic model to identify appropriate environmental flow objectives. The hydraulic model and hydrological statistics were then used to recommend the magnitude, duration, frequency and timing of flows required to meet the objectives.

The study of Jiang et al. (2010) made the following recommendations:

- low baseflow of 270 m3/s in November to March
- medium baseflow of 480 m3/s in April to June
- flow pulse of 4 days duration at 2200 m3/s in early April
- flow pulse (1–2 per year) of 2 days duration at 2200 m3/s in April to June
- high flow (2–4 per year) of 5 days duration at 4000 m3/s in July to October.

Just prior to the publication of Jiang et al. (2010), the same authors published a similar paper in Chinese (Jiang et al. 2009). The earlier paper included three additional environmental flow options (termed scenarios) that involved reduced magnitudes for the flow components listed above (except for the high-flow component, which had two additional options). The basis for reducing the flow magnitudes was not indicated and the ecological consequences were subjectively described, rather than being based on a quantitative risk assessment.

4.3.3 Hydrology research

Ni and Qian (2002) referred to the French ordinance that stipulates that the minimum ecological water demand should not be less than 10 per cent of the annual average discharge.[10] Based on this standard, the critical discharges in the four reaches of the Lower Yellow River were estimated at 157.2 m^3/s for Sanmenxia to Huayuankou reach, 154.1 m^3/s for Huayuankou to Gaocun reach, 158.0 m^3/s for Gaocun to Aishan reach and 155.6 m^3/s for Aishan to Lijin reach.

Tennant (1976) related discharge to fish habitat quality through the correlation of physical, geometric and biological parameters to discharge. Tennant (1976) then related the percentage of the mean annual unimpaired discharge to a scale of fish habitat qualities. Tennant (1976) split his flow recommendations into two different seasons, October to March (low-flow season) and April to September (high-flow season). The method was originally called the 'Montana method' by Tennant because it was created using data from the Montana region, and was developed through field observations and measurements from 58 cross-sections and 11 streams in Montana, Nebraska and Wyoming. A study by Mann (2006) of 161 sites spread across the western U.S. found that:

> '*The current form of the Tennant method does not necessarily protect habitat adequately because the channel characteristics (width, depth, and velocity) that Tennant-based habitat quality on are not consistent across stream types in the western U.S… For the Tennant method to be used as purposed in 1976, this study recommends that the method be applied with caution or modified to better represent local conditions based on further research. Future research needs to validate the physical channel characteristics (width, depth, and velocity) needed to support desired fish habitat levels. This will provide the support needed to use the Tennant method in any situation where the instream flow recommendations need to be defended… it is recommended that the Tennant method be used only for initial planning flow recommendations without serious validation within the region of use… The defense of any specific flow recommendation produced solely through the use of the Tennant method, outside of Tennant's study area and the characteristics validated in this study (temperate desert division streams, and low gradient streams), is diminished by the data produced in this study and therefore should be treated as potentially suspect without further validation*.'

In terms of hydrological, geomorphological, hydraulic and ecological characteristics, no suggestion has been made that the 11 streams used to formulate the Tennant method share similarities with the lower Yellow River. In fact, similarities never been demonstrated for any river in China. The data of Mann (2006) clearly demonstrated that the Tennant method is not transferrable to other rivers within the western USA, so the chance of it being transferrable to rivers in China would seem to be remote.

In their application of the Tennant method to assess flow needs for the lower Yellow River, Liu et al. (2006) did not actually use the Tennant method as described by Tennant (1976). The method of Tennant multiplies mean annual flow (MAF) by various factors depending on the desired stream health, and recommends only three flow components: baseflows for the low-flow season, baseflows for the high-flow season and a flushing flow of 4 to 6 days duration (Table 5). The period of record used to calculate the MAF should represent unregulated conditions. The flushing flow component of the Tennant method was not included by Liu et al. (2006)[11], but they did include a sediment scouring flow that was calculated using a different method. In the study of Liu et al. (2006), a minimum flow was calculated for each month (Tennant used only two seasons) as a percentage of the historical mean monthly discharge (Tennant used annual discharge) in the benchmark time series, which was taken to be 1956– 1985. The calculation was based on 20 per cent of the mean monthly flow, and in reaches with certain high value ecological assets, the values for April, May and June (spring), were based on 40 per cent of mean monthly discharge (Liu, 2006) (Table 3). Superficially, these

10 Hirji and Davis (2009) explained further that, in France, the environmental flows from dams must be a minimum of 2.5 per cent of the mean annual flow for existing schemes and 10 per cent of the mean annual flow for new schemes.

11 The flushing flow component is usually disregarded in applications of the Tennant method in China.

factors may appear to align with Tennant's stream condition class 'good' (Table 5). However, where Tennant's 'good' requires 30 per cent of the mean annual discharge for baseflows, the baseflow regime of Liu et al. (2006) requires only 17 per cent of modelled natural MAF at Huayuankou and 15 per cent of modelled natural MAF at Lijin.[12] This percentage of MAF lies between 'poor or minimum' and 'fair or degrading' in Tennant's scale (Table 5).

Table 5. Instream flow for fish, wildlife, and recreation recommended by Tennant (1976).

Narrative description of flows*	Recommended regimens		Per cent of annual flow
	Oct-Mar	Apr-Sep	
Flushing or maximum	200% of MAF for 48–72 hours		1.1–1.6%
Optimum range	60-80% of MAF		60–80%
Outstanding	40%	60%	50%
Excellent	30%	50%	40%
Good	20%	40%	30%
Fair or degrading	10%	30%	20%
Poor or minimum	10% of MAF		10%
Severe degradation	10% of MAF to zero flow		0–10%

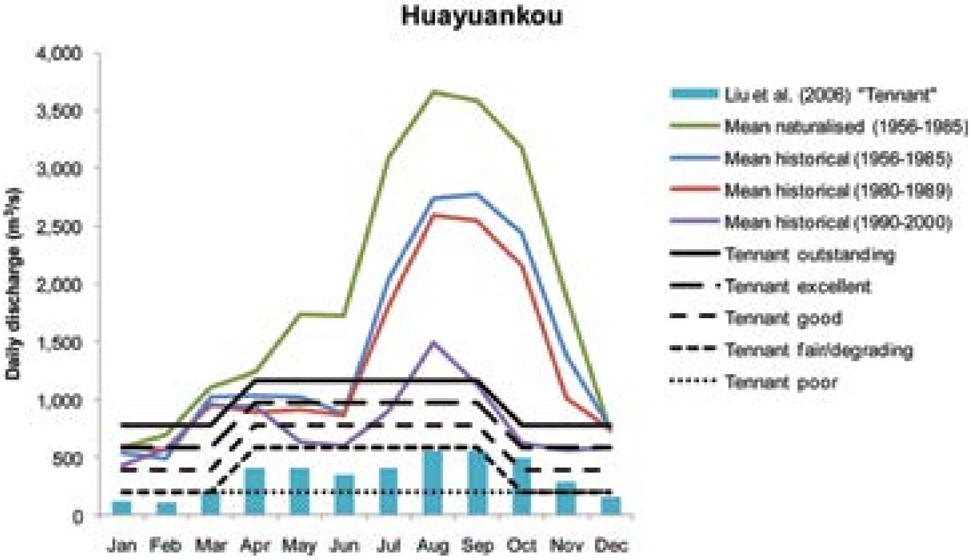
* Most appropriate description of the general condition of the stream flow for fish, wildlife, recreation and related environmental resources. Right-hand column was not included in Tennant (1976).

For Huayuankou and Lijin, a comparison was made between the recommendations of Liu et al. (2006) and recommendations based on the Tennant method as originally described by Tennant (1976) (Figure 9 and Figure 10). This comparison revealed that the seasonality of the Tennant method does not fit perfectly with that of the lower Yellow River. Because the Tennant method is based on factoring the mean annual flow, it produces flow recommendations for each month of the low-flow season that are closer to the mean monthly flows, compared with those of the high flow months (Figure 9 and Figure 10). Allocating a higher percentage of natural flows to the low-flow months is an important characteristic of the Tennant method – the factors were derived from calibration of the mean annual flow statistic to observed ecological health data (had Tennant used mean monthly flows, then the factors would have been different). The recommendations of Liu et al. (2006) for all months except October and November fell below Tennant's 'fair or degrading' category, which on Tennant's scale is referred to as 'severe degradation'. A key reason the values calculated by Liu et al. (2006) were low compared to the intentions of the original Tennant method is because Liu et al. (2006) used a significantly modified historical flow series (1956–1985) as the benchmark (Figure 9), while Tenant (1976) recommended use of an unimpaired time series (i.e. the naturalised series, or data from an unregulated period).

For Lijin, the recommendations of Liu et al. (2006) for April, May and June were similar to the monthly mean flows for the 1980s and 1990s (Figure 10). However, for most of the year the recommended flows were significantly lower than the monthly mean flows in the 1990s (Figure 10), when the river was known to have suffered poor river health. On the other hand, for Lijin, the flows recommended for 'good ecosystem health using the original Tennant method were higher than historical mean flows for the 1980s and 1990s for the 7-month non-flood season from December to June (Figure 10).

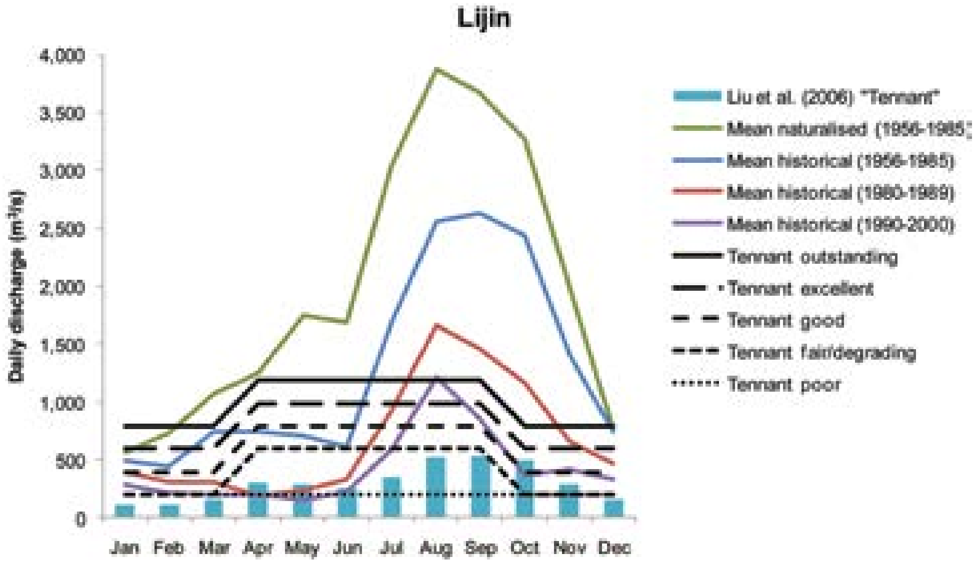
12 Calculated as a percentage of mean annual historical flows from 1956 to 1985, the baseflow recommendations of Liu et al. (2006) require 23 per cent of MAF for both Huayuankou and Lijin.

Figure 9. Estimated environmental flows for ecosystem protection on the Yellow River at Huayuankou using the (original) Tennant method (1976) and using a modified Tennant method by Liu et al. (2006).



Notes: Tennant method based on factored naturalised mean annual flow Liu et al. (2006) used a modified Tennant method using factored historical monthly flows (1956-1985). For reference, the monthly means of the naturalised flow series (1956–1985) and the monthly means of the historical flow series for three periods are shown.

Figure 10. Estimated environmental flows for ecosystem protection on the Yellow River at Lijin using the (original) Tennant method (1976) and using a modified Tennant method by Liu et al. (2006).



Notes: Tennant method based on factored naturalised mean annual flow Liu et al. (2006) used a modified Tennant method using factored historical monthly flows (1956-1985). For reference, the monthly means of the naturalised flow series (1956–1985) and the monthly means of the historical flow series for three periods are shown.

Huang Q et al. (2007) and Wang et al. (2009) also modified aspects of the Tennant method and applied it to the lower Yellow River. The monthly and seasonal flow factoring used by these authors produced recommendations for the non-flood season that were considerably lower than if estimated using the original Tennant method. There are other methodological papers published in Chinese journals that describe modifications to the original Tennant method, with the authors claiming that their revised methods are superior to the original (e.g. Guo et al. 2009; Tian et al. 2010).[13]

13 Suggestions to modify the Tennant flow-factoring scheme are not new. For example, for New Zealand rivers, Fraser (1978) suggested specifying monthly minimum flows as a percentage of monthly mean flows.

For example, Tian et al. (2010) correctly argued that for seasonal rivers, the median is a better measure of central tendency than the mean, and formulated flow recommendations using the proportions recommended by Tennant using the median, long-term annual discharge rather than the mean. Of course, this gave significantly lower values for environmental flow, which prompted Tian et al. (2010) to claim:

> '*The results show that the improved Tennant method is more reasonable than the conventional method results… [and]…the improved method of the ecological water use is more realistic than the traditional one. According to the actuality of water resources, this improvement is helpful to sustainable development…This study provides a new idea for further improvement of the Tennant method in order to protect ecological environment.*'

From the perspective of protection of ecological health, such claims are baseless, because neither the flow levels recommended by the original Tennant method, nor the modified method, have been related to any ecological data from the rivers in question. Thus, modifications to the Tennant method are merely academic exercises, and their application to Chinese rivers is no more valid than application of the original method.

The Tennant method has been widely applied China (Wang et al. 2007; Wang et al. 2009) – that is the Tennant method, in its original form or any other method that involves deriving flow recommendations simply by multiplying a flow statistic (such as mean or median monthly, seasonal or annual flow) by an arbitrary factor. The resulting recommended flows have no known correlation with ecological health of the rivers being assessed. Therefore, using this approach should be regarded as high-risk and difficult to defend from a scientific perspective.

4.3.4 Holistic research

Holistic studies consider the full variety of the flow requirements, of multiple ecosystem values and processes at multiple sites in an integrated way. Most holistic studies attempt to develop models that relate aspects of the flow regime to ecological health outcomes. Three holistic studies are reviewed in this section:

1. Ni et al. (2002), also reported in Ni and Qian (2002)
2. Liu et al. (2008)
3. Zhao W (2010).

The work of Liu et al. (2006) also falls within the category of holistic research and was reviewed in a previous section of this report. A weakness of the work of Liu et al. (2006), and Ni et al. (2002) is that the ecosystem needs were based on a simple factoring of hydrology statistics that had no known correlation with ecological outcomes.

Study of Ni et al. (2002)

Ni et al. (2002) estimated the thresholds of water demands for pollution self-purification, ecological protection, sediment transportation and estuarine conservation using historical data from 1950–1998. Self-purification was based on achieving Grade III water quality. Water for the ecosystem was based on providing 10 per cent of the annual discharge as a mean daily minimum. The critical discharge for sediment discharge was based on concepts of sediment transport efficiency. Water for estuarine conservation was based on a number of considerations. Ni and Qian (2002) referred to a demand made in the mid -980s by the State Aquaculture Bureau for 6 × 10^9 m^3 runoff into the sea from April to July in ordinary years and 2 × 10^9 m^3 runoff in April in dry years. The dry year April demand equates to a monthly average of 771.6 m^3/s at Lijin. Ni and Qian (2002) cited He (1998), who estimated that the critical sediment concentration for delta progradation was 10 g/L. Ni and Qian (2002) concluded that the flows estimated to have the capacity to transport sediment through the lower river would be sufficient to ensure delta growth. A combined environmental flow regime was recommendation that would satisfy all of these individual needs (Table 6).

Table 6. Critical discharges to meet multi-criteria environmental flow objectives

Gauging station	Reach	Critical discharge (m^3/s)		Runoff (10^9 m^3)	
		Flood season	Non-flood season	Non-flood season	Annual
Huayuankou	Sanmenxia-Huayuankou	1972 – 2042	232	4.80	25.25 – 25.97
Gaocun	Huayuankou-Gaocun	2322 – 2684	234	4.86	28.93 – 32.69
Aishan	Gaocun-Aishan	2191 – 2640	158	3.28	25.99 – 30.64
Lijin	Aishan-Lijin	2140 – 2520	156	3.23	25.42 – 29.35

Source: Ni and Qian (2002). Note: discharges have been rounded to nearest m^3/s.

Study of Liu et al. (2008)

Liu et al. (2008) followed up the work of Liu et al. (2006) with a holistic study that considered flows for sediment transport, maintaining at least Grade III water quality and for maintaining habitat for fish and birds in the delta. One of the key differences between these two studies is that Liu et al. (2008) identified key assets and based the initial estimation of flow needs on the hydraulic requirements of the biota, while Liu et al. (2006) used a simple flow factoring approach. Liu et al. (2008) produced two options for each station: a ‘minimum flow’ and a ‘suitable flow’. These flows can be interpreted to mean a survival flow only for short-term use and ecologically sustainable flow that will maintain ecological integrity. A characteristic of the study of Liu et al. (2008) is trying to reach a compromise between social needs and environmental needs. The methodology for this approach does not appear to be repeatable, i.e. it is not based on objective functions. Also, one objective of Liu et al. (2008) was to provide a flow that would maintain the fish and birds to the early 1990s level of health. However, by the early 1990s at Lijin, both the baseflow and flow events were severely reduced in magnitude compared to pre-regulation levels through the impacts of dams and diversions (see section 6 of this report on hydrology). In the early 1990s, the ecology may still have been in reasonable health, but published data to support this assumption is unknown. Given the degree of hydrological alteration, morphological alteration, and poor water quality, it is likely that the ecological health of the river was significantly impaired in the early 1990s.[14]

The flow recommended by Liu et al. (2008) for channel maintenance and sediment transport was based on Liu et al. (2006). Therefore, the recommendation was to achieve a target channel capacity of 4000 m^3/s with a flow of at least 3500 m^3/s at Huayuankou. It was also recommended that flows in the range 800–2600 m^3/s at Huayuankou should be avoided, as this flow range can mobilise sediment in the upper reaches, but may be inadequate to maintain the transport of this sediment through the entire lower reach to the mouth. Also, at flow rates less than 2600 m^3/s, if sediment concentration exceeds 20–25 kg/m^3, the river is not fully competent to transport the sediment and some of it will deposit on the bed.

For water purification, a one-dimensional model was used to predict the discharge required to maintain COD concentrations within Grade III standard. The recommendations were 300 m^3/s for Xiaolangdi and 320 m^3/s for Huayuankou. Minimum flows for water quality maintenance were also suggested – 160 m^3/s for Xiaolangdi and 170 m^3/s for Huayuankou.

Flows for the ecology were based on the requirements of birds, wetland vegetation and fish in the Yellow River Delta National Nature Reserve, with a focus on high conservation value species and their habitats. In the past, before regulation, the reed habitats would flood naturally, but currently the water delivery to wetlands is controlled. Flow recommendations for total volume of water inflows were based on known water depth requirements for vegetation and important birds (Table 7), models of the area of different vegetation types inundated as a function of inflowing water, and empirical relationships of bird numbers as a function of inflowing water volume.

Table 7. Depth requirements for birds and reed (*Phragmites*) vegetation in the Yellow River delta environment.

Season	Mean depth (m)	Depth range (m)	Main ecological function
Apr–Jun	0.3	0.1–0.5	Germination and growth of reed
Jul–Oct	0.5	0.2–0.8	Reed growth and important birds
Nov–Mar	0.2	0.1–0.2	Wintering habitat for important birds

Source: Liu et al. (2008).

The needs of fish were based on the hydraulic habitat needs and hydrological needs for fish to complete their life cycles (Table 8). Spawning season is May–June and the main rearing season is June–October. Required water depth in the river main channel is 1–2 m, and the preferred flow rate is 0.3–0.6 m/s. Based on this information, the flows required to provide habitat were calculated for the reach from Lijin to the sea (Table 9). On the basis of the modelled result, and other considerations, such as peak irrigation requirements in March–May, a compromise flow regime for fish was suggested (Table 10). A further iteration was then undertaken to produce a final set of flow recommendations (Table 11).

14 Any state of river health (from poor to good) can be a valid river management target, but river managers and stakeholders should be fully aware of the relative state of river health embodied in the management objectives. For example, river health as it was in the 1990s is a reasonable objective, but for it to be a practical management target, the 1990s level of river health should be described in objective terms (such as diversity and abundance of flora and fauna).

Table 8. Ranges of velocity and depth observed at different discharges at the river mouth, and their suitability for fish spawning and survival.

Discharge (m^3/s)	Velocity (m/s)	Depth (m)	Main ecological function
50	Max. 0.5	Greater than 1	Barely meet the needs of wintering fish
100	Mean 0.4–0.6	Mean 1–2	Superior conditions for fish during winter; barely meet the requirements of fish for spawning
150	Mean 0.5–0.7 Max. 0.6–1.3	Mean 1–2	Meet the spawning requirements of the majority of fish
200	Mean 0.5–0.8 Max. 0.7–1.5	Mean 1.2–2.0 Max. 1.5–4.0	Superior conditions for fish for spawning

Source: Liu et al. (2008).

Table 9. Modelled flow rates required for fish in the Lijin section.

	Jan	Feb	Mar	Apr	My-Jun	Jul-Oct	Nov	Dec
Minimum (m^3/s)	70–80	70–80	70–80	70–80	150	200–300	70–80	70–80
Suitable (m^3/s)	120	130	170	190	250	500–700	290	130

Source: Liu et al. (2008).

Table 10. Suggested environmental flow regime for fish in the Lijin section.

	Jan–Apr	May–Jun	Jul–Oct	Nov–Dec
Minimum (m^3/s)	75	150	Baseflow 200 Flood flow ≥ 3500	75
Suitable (m^3/s)	120	250	Baseflow 300 Flood flow ≥ 3500	120

Source: Liu et al. (2008).

Table 11. Suggested minimum and appropriate environmental flow regime options for the lower Yellow River.

	Jan - Mar	Apr	May–Jun	Jul–Oct	Nov	Dec
Huayuankou						
Minimum (m^3/s)	170	200	200	300	170	170
Suitable (m^3/s)	320–900	320–900	320–900	400	Baseflow 320–900 Flood flow ≥ 3500	320–900
Lijin						
Minimum (m^3/s)	75	75	150	200	75	75
Suitable (m^3/s)	120–200	120	250	300	Baseflow 120 Flood flow ≥ 3500	200

Source: Liu et al. (2008).

Study of Zhao W (2010)

Zhao W (2010) recently undertook a holistic study of the environmental flow needs of the lower Yellow River. The study assessed the needs of macrozoobenthos, fish, and riparian vegetation using a range of methodologies. Although the study falls within the holistic category, it included only a cursory consideration of geomorphological processes, and did not consider water quality or estuary needs in any detail.

The environmental flow requirements of macrozoobenthos were assessed at Huayuankou using a hydraulic habitat simulation method. Distribution of macrozoobenthos in different habitat types (edge, riffle, pool and run) was investigated, and edge and riffle habitat type were identified as the optimum habitat types for macrozoobenthos. An optimum discharge of 400–600 m^3/s in the non-flood season was determined (Zhao W, 2010).

The environmental flow requirements of fish were examined at Huayuankou using a hydraulic habitat simulation method, combined with a building block approach that considered the hydrological and hydraulic life cycle needs of a key fish species. The Yellow River carp was selected as the indicator species. A 2-D hydraulic model was used to simulate the adult habitat area, juvenile habitat area and spawning habitat area across a range of discharge. Adult and juvenile fish habitat requirements were met at discharges between 300 and 1000 m^3/s. A discharge greater than 1500 m^3/s was adequate for meeting the requirements of fish spawning (Zhao W, 2010).

The environmental flow requirements of riparian vegetation were investigated in the lower reaches of the Yellow River using a building block method. A total of 105 plant species were identified from five sites. Three species (*Potentilla upine*, *Rumex dentatus* and *Mariscus compactus*) were selected as indicators. Based on the distribution (elevation and distance from the water's edge) of plants, an optimum discharge of about 350 m^3/s was established. Plants have different flow requirements in different life stages: high flows or flow freshes in between March and April raise the soil moisture, and medium flows between May and June maintain soil moisture required for plant growth. Constant flows between July and September were considered to be important for flowering and fruiting, and a flow fresh between October and November was included to disperse seed. Lower flow was considered important during the December to February period of seed dormancy (Zhao W, 2010).

Comprehensive analyses of the flow requirements of macrozoobenthos, fish and riparian vegetation by Zhao W (2010) derived an environmental flow regime for Huayuankou that included the following key components:

- low baseflows of 300 m^3/s in December to February
- medium baseflows of 400-600 m^3/s in late-March to early-July and middle-September to December
- high baseflows of 2000 m^3/s in late-July to early-September, plus a short duration (about ten to fifteen days) high flow of 4000 m^3/s for channel maintenance and sediment transport
- a pulse greater than 1500 m^3/s around mid-April for ten to fifteen days (combined with a water temperature range 18–25°C) for fish spawning
- a pulse in late October for seed dispersal.

Zhao W (2010) focused his detailed investigations at Huayuankou and in the lower reaches of the river. He translated the results to Gaocun, Aisha, and Lijin using a hydrological method (factoring hydrological statistics, as in the Tennant method). It was determined that baseflow discharges should be 346–538 m^3/s at Gaocun, 326–507 m^3/s at Aisha, and 246–382 m^3/s at Lijin.

Chapter 5. Geomorphology

5.1 Modern geomorphic history

From Mengjin to the sea, the lower Yellow River falls about 120 m. The high sediment load of the river creates naturally high rates of channel mobility. Over time, flood sediments have preferentially deposited close to the channel, building the channel higher in elevation than the surrounding floodplain. Therefore, the channel is naturally prone to avulsion (course change) during floods. Over the past 3500 years, the channel has undergone several major avulsions, and other minor changes of direction, spread over a width of 400 km (Li and Finlayson 1993; Pietz and Giordano 2009). In 1938, the southern dike at Huayuankou was intentionally breached, and for nine years the river shifted its course over the Great Plain to the south-east. The Huayuankou breach was closed in 1947 and the river returned to its post-1855 (and current) course (Li and Finlayson 1993). The current course downstream from Dongbatou resulted from a major avulsion in 1855, while the reach from Huayuankou to Dongbatou is less than 550 years old (Shi 2005). The high sediment load of the river has also created a delta environment characterised by rapid rates of progradation into the sea, and numerous shifts of mouth position (Chu et al. 2006; Fan et al. 2006).

Construction of protective dikes along the margins of the lower Yellow River channel began in the Warring States Period (475–221 BC). This construction was to reduce the risk of channel instability and floods, making permanent settlement and cultivation possible (Shi and Ye 1997). The current dikes of the lower Yellow River protect its entire length, except in places where the river abuts the valley wall. The dikes extend for a total length of 1369.5 km and protect an area of at least 12,000 km^2 (Shi and Ye 1997), and up to 49,000 km^2 (ADB 2001), from floods. After the dikes were constructed, the bed of the river rose in elevation as more sediment was deposited than was scoured. This increased the flood risk, so dikes were progressively built higher and were better fortified. Since founding of the People's Republic of China in 1949 the dikes have been strengthened and raised four times, by about 1 m on each occasion (Li and Finlayson, 1993; Liu, 1989). The result is that the current river bed is higher in elevation than the surrounding plain, by up to 10 m in places (Pietz and Giordano 2009).

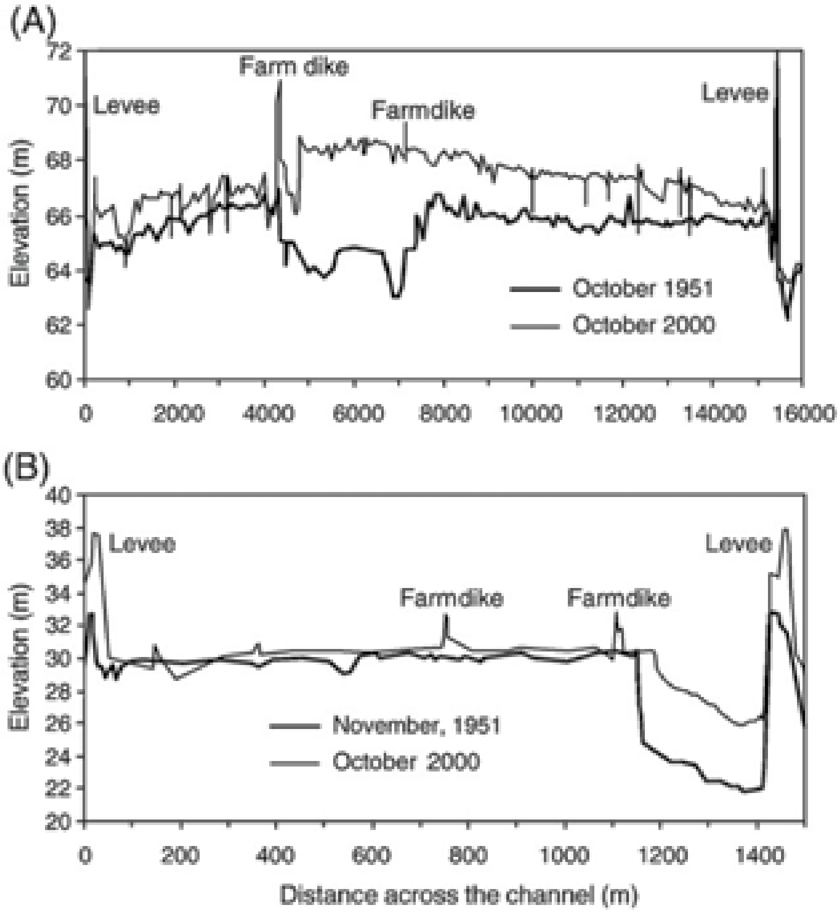
The lower Yellow River has four main zones of planform morphology (Figure 4) that reflect the balance of sediment supply, transport capacity and river training efforts. The upper zone from Xiaolangdi to Gaocun is characterised by a plentiful supply of sediment and higher gradient, and it is braided. From Taochengpu to the estuary, the river has a lower gradient and follows a meandering course. In between the river is transitional between braided and meandering. The estuary and delta represents the fourth distinct zone.

Starting from 1950, extensive river training has been carried out in the Lower Yellow River to deal with flood flows and sediment problems (Wu et al. 2005). The strategy is to confine large floods within a wide floodplain controlled by the dikes, to use an inner main channel controlled by river training works to transport sediment, and to guide the flow away from the dikes (Li et al. 2002). The ultimate goal of this strategy is to change the upper zone from an actively braided channel into a confined meandering channel (Wu et al. 2005).

In general, the wide floodplain between two main flood dikes may once have been inundated during the three wet months (August, September, and October) and been fully exposed for the other nine months (Yu 2006). Over time, as the flood frequency and peak flow rate reduced due to regulation of the river, the wide flats were inundated less frequently, which encouraged farmers to move from outside the dikes and cultivate crops on the inner floodplain. The population living on the inner floodplain is about two million residents (ADB 2001; Yu 2006). To protect themselves from high flow events, the farmers built inner dikes, known locally as production dikes (Yu 2006) or farm dikes. Over time, in some parts of the river, the channel bed built up within the inner dikes, creating a 'secondary hanging river' (Figure 11). Currently, the channel bed level within the production dikes has been elevated by accretion to 3–5 m higher than the level of the outer flats; and this outer flat level is, in turn, 5–6 m higher than the ground surface beyond the flood dikes (Yu 2006). Yu (2006) estimated that the length of the secondary hanging river form was 280 km, extending 80 km upstream of Dongbatou (to Kaifeng) and 200 km downstream (to Sunkou).

The meandering reach below Taochengpu was well controlled by river training works early in 1958. In the transitional reach, from Gaocun to Taochengpu, most river training works were constructed from 1966 to 1974, and the transitional channel pattern now more resembles a confined meandering pattern (Wu et al. 2005). River training works have been carefully extended to the braided reach from Tiexie to Gaocun. In areas where the works have been completed, the degree of braiding has been reduced and the shifts in channel position have been limited (Wu et al. 2005).

Figure 11. Typical cross-sectional profiles of the lower Yellow River.



Notes: A. Mazhai, 274 km downstream of Xiaolangdi Dam, a typical section on the lower end of the braided reach
B. Luokou, 529 km downstream of Xiaolangdi Dam, a typical section on the meandering reach.
Source: Wu et al. (2008).

The meandering reach below Taochengpu was well controlled by river training works early in 1958. In the transitional reach, from Gaocun to Taochengpu, most river training works were constructed from 1966 to 1974, and the transitional channel pattern now more resembles a confined meandering pattern (Wu et al. 2005). River training works have been carefully extended to the braided reach from Tiexie to Gaocun. In areas where the works have been completed, the degree of braiding has been reduced and the shifts in channel position have been limited (Wu et al. 2005).

5.2 Reach characteristics

The four reaches have distinctive geomorphic characteristics (Table 12). The channel becomes narrower and deeper in the downstream direction, and the distance between the dikes also narrows. The channel also becomes less steep in the downstream direction.

Xiaolangdi to Gaocun

The first 40 km long section of river is naturally contained by valley walls (Figure 12). Mengjin Huanghe Nature Reserve is located within this section. The dikes begin on the left bank (northern side) at about 40 km, and on the right bank (southern side) just upstream of Zhengzhou. The cross-section form of the river valley in the Mengjin to Gaocun section varies (Figure 13, Figure 15 and Figure 17). In the upper part near Mengjin the river flows between the valley walls and is not perched (Figure 13), because sediment deposition is not constrained by dikes. Downstream of Zhengzhou the river flows between dikes, and the channel is perched above the elevation of the valley beyond the dikes (Figure 14, Figure 15). In the vicinity of Kaifeng (Figure 16) the river is perched around 10 m above the land beyond the dikes (Figure 17).

Gaocun to Taochengpu

Between Gaocun and Taochengpu the channel contains some sharp bends, as its position is controlled by groynes (Figure 18). The channel is perched, but to a lesser degree than at Kaifeng (Figure 19).

Taochengpu to estuary

In the vicinity of Jinan, the river runs close to the valley wall on the southern side (Figure 20). The degree to which the channel is perched is less than the reach upstream (Figure 21). Towards Lijin (Figure 22), the channel is deep and narrow, but flows with a diked section that is perched above the surrounding land (Figure 23).

Table 12. Geomorphological characteristics of the four reaches assessed for environmental flow requirements.

Reach	Plan form	Length (km)	Channel width (km)	Channel depth (m)	Width/ Depth	Slope	Sinuosity	Distance between flood dikes (km)	Elevation of bed above floodplain (m)
Xiaolangdi – Gaocun	Braided	207[a] 264[b] 299[c] 286[d]	1.0–3.5	2	662[h] 736–884[i]	0.000265-0.000172	1.15[h]	5–20	2[e]
Gaocun – Taochengpu	Transitional	165	0.5–1.6	2-3	163[h] 230[i]	0.000115	1.33[h]	1.4–8.5	2–3[b]
Taochengpu – estuary	Meandering	384[f]	0.3–0.8	2-3	126[h] 78[i]	0.000100	1.21[h]	0.45–5.0	3–4[b]
Estuary – Bohai	Meandering/ channelised	20	0.15–0.5	–	–	0.000060[g]	–	No dike	–

Primary source is Yu (2006), with other sources listed below:
a. Wu et al. (2008a) from Taohuayu (Qin River junction)
b. Yu (2006) from Mengjin
c. Wu et al. (2005) from Tiexie
d. Xia et al. (2008) from Mengjin
e. Xia et al. (2008)
f. Estimated from total length from Taochengpu to estuary of 404 km, assuming estuary length of 20 km
g. Yu (2002)
h. Xu (2003)
i. Xu (2005b).

5.3 Sediment particle size

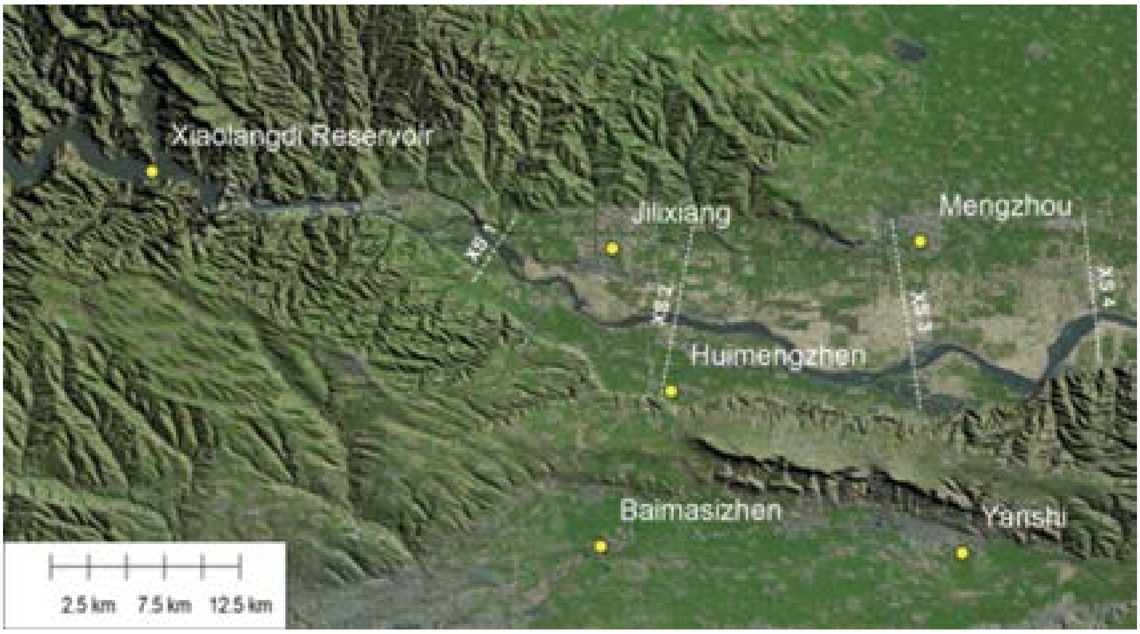
Loess generates mostly fine-grained sediment. In the lower Yellow River, the fractions of suspended sediment larger than 25 μm are conventionally regarded as bed-material load, and the fractions smaller than 25 μm as wash load (Xu and Cheng 2002; Xu et al. 2009). The size fraction of most concern with respect to sedimentation of the river bed is that coarser than 50 μm (Xu et al. 2009).

The coarse fraction of the suspended load of the lower Yellow River comes mainly from the drainage area between Hekouzhen and Longmen and the Beiluohe and Malainhe River basins in the middle reaches of the Yellow River basin (Xu et al. 2009). Xu (1999) and Xu (2005b) reported that over the period 1960–1990 at Longmen station, in the middle Yellow River, the percentage of the suspended sediment that was coarser than 50 μm ranged from 20 to 43 per cent, with a very close and positive correlation between sediment coarseness and the total sediment load. Thus, the grain size followed the same declining trend in sediment loads since the late 1960s. Before 1960, the percentage of the suspended sediment load coarser than 50 μm was even higher, being around 50 per cent of the total; of this material, about 83 per cent was deposited on the bed (Xu et al. 2009).

Using data from 1962 to 1985, Xu et al. (2009) found that of the sediment input to the lower Yellow River larger than 25 μm, 44 per cent was deposited in the channel; of the sediment input larger than 50 μm, 77 per cent was deposited in the channel; and of the sediment input larger than 100 μm, 98 per cent was deposited on the channel. One of the expected benefits of Xiaolangdi Reservoir would be ‘trapping the coarse sediment and releasing the fine’, reducing sedimentation of the lower river channel (Xu et al. 2009).

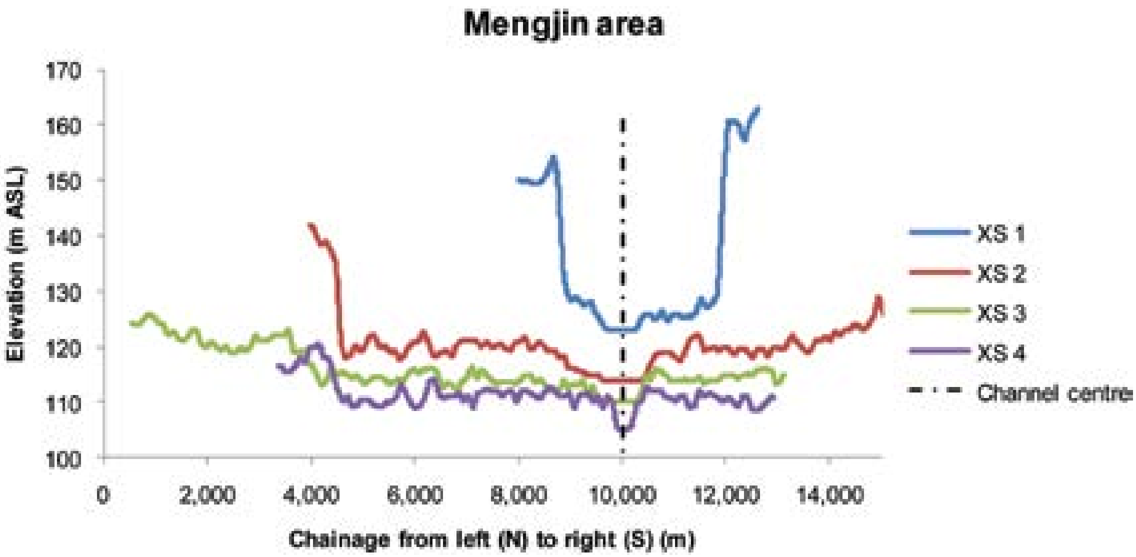
He et al. (2010) sampled the suspended sediment in the lower Yellow River at Lijin throughout the water sediment release from 15 June to 5 July 2005, and then continued sampling opportunistically until 18 July 2005 to characterise the effect of a rainstorm-induced flow event. Over the total period, clay and very fine silt (< 8 μm) dominated the load, representing 30 to 70 per cent of the total, while the sand fraction (> 63 μm) never exceeded 10 per cent. The contribution of the fine silt fractions (8–16 μm) ranged from 20 to 30 per cent, whereas medium silt (16–32 μm) ranged from 10 to 30 per cent, and coarse silt (32–63 μm) ranged from less than 5 to 20 per cent. The proportion of clay and very fine silt was higher in the rainstorm than in the WSDR event, and the rainstorm event transported very little sand. The suspended material in the rainstorm event was sourced from catchment slopes, while the material in the WSDR event was mostly scoured from the Yellow River channel itself.

Figure 12. Upper section of reach 1 from Xiaolangdi to Gaocun, just downstream of Xiaolangdi Dam.



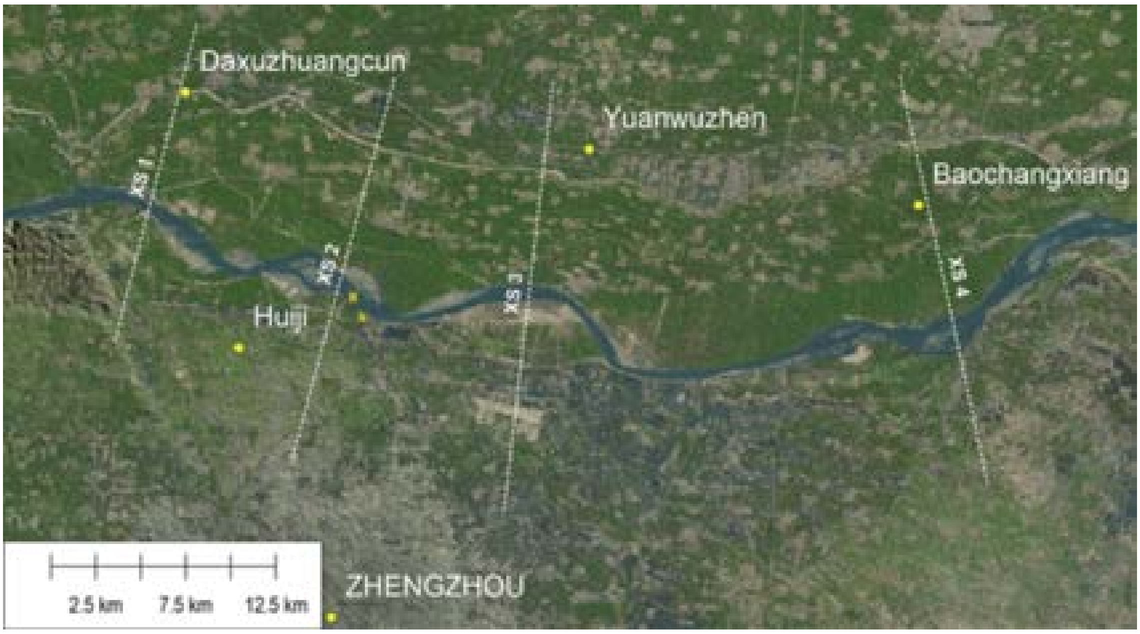
Note: The Mengjin Huanghe Nature Reserve is located within this section of river. Locations of XS 1 to XS 4 are arbitrary. Landsat 7 true colour image (www.resmap.com) superimposed onto hill-shaded SRTM DEM (www2.jpl.nasa.gov/srtm/).

Figure 13. Upper section of reach 1 from Xiaolangdi to Gaocun near Mengjin, cross-section morphology.



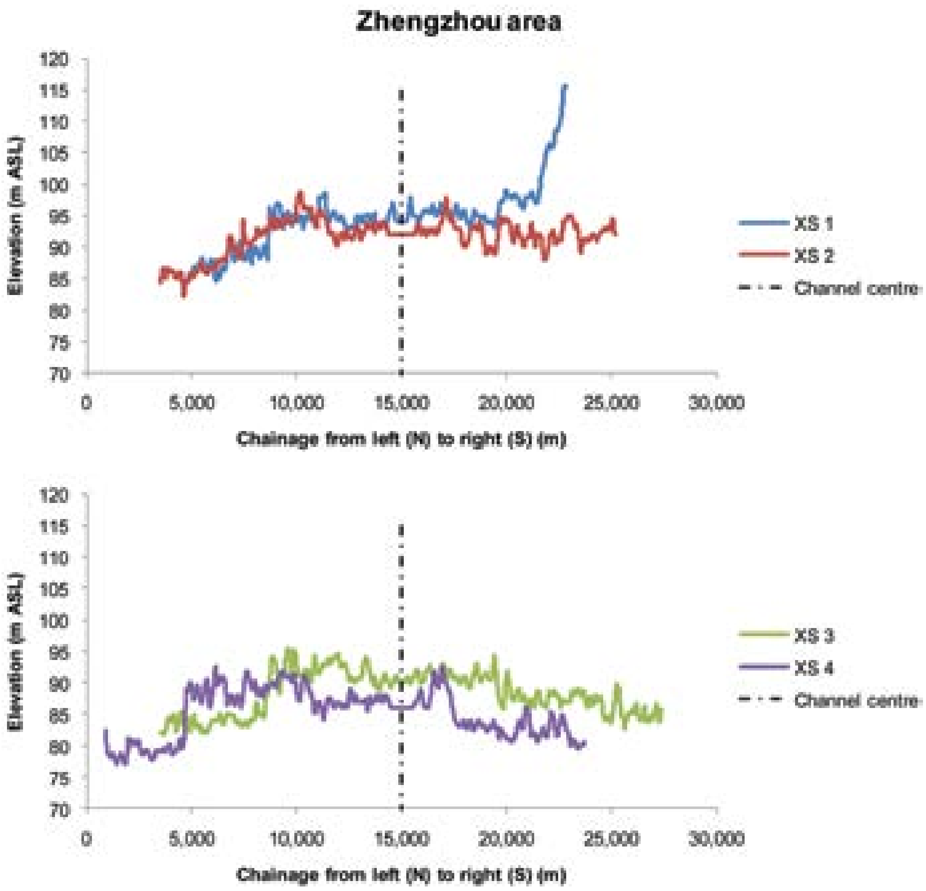
Note: For locations of XS 1 to XS 4, see Figure 12. Cross section extracted from SRTM DEM (www2.jpl.nasa.gov/srtm/). Channel represented by water surface elevation.

Figure 14. Upper section of reach 1 from Xiaolangdi to Gaocun, near Zhengzhou.



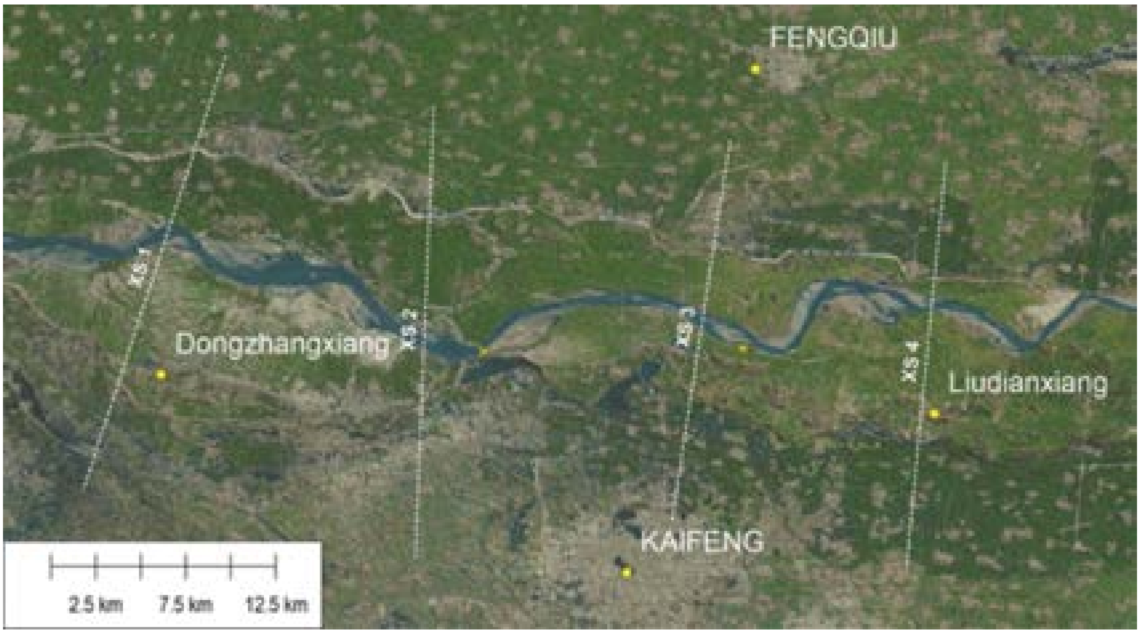
Note: The Zhengzhou Huanghe Wetland Nature Reserve is located within this section of river. Locations of XS 1 to XS 4 are arbitrary. Landsat 7 true colour image (www.resmap.com) superimposed onto hill-shaded SRTM DEM (www2.jpl.nasa.gov/srtm/).

Figure 15. Upper section of reach 1 from Xiaolangdi to Gaocun near Zhengzhou, cross-section morphology.



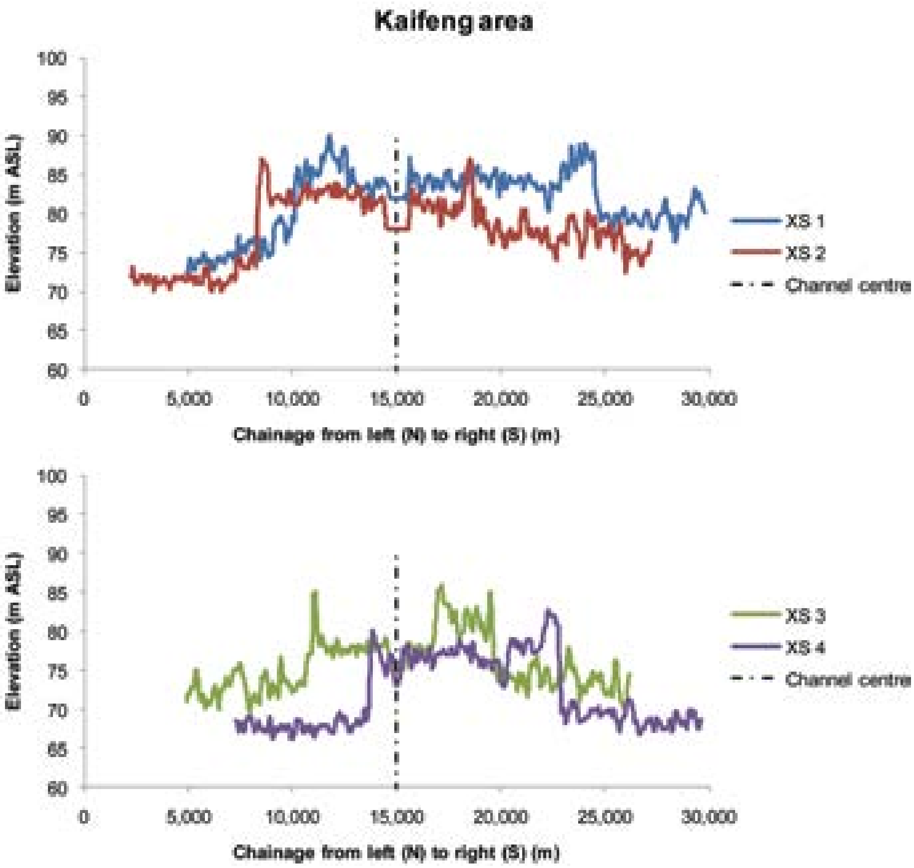
Note: For locations of XS 1 to XS 4 see Figure 14. Cross-sections extracted from SRTM DEM (www2.jpl.nasa.gov/srtm/). Channel represented by surface water elevation.

Figure 16. Middle section of reach 1 from Xiaolangdi to Gaocun, near Kaifeng.



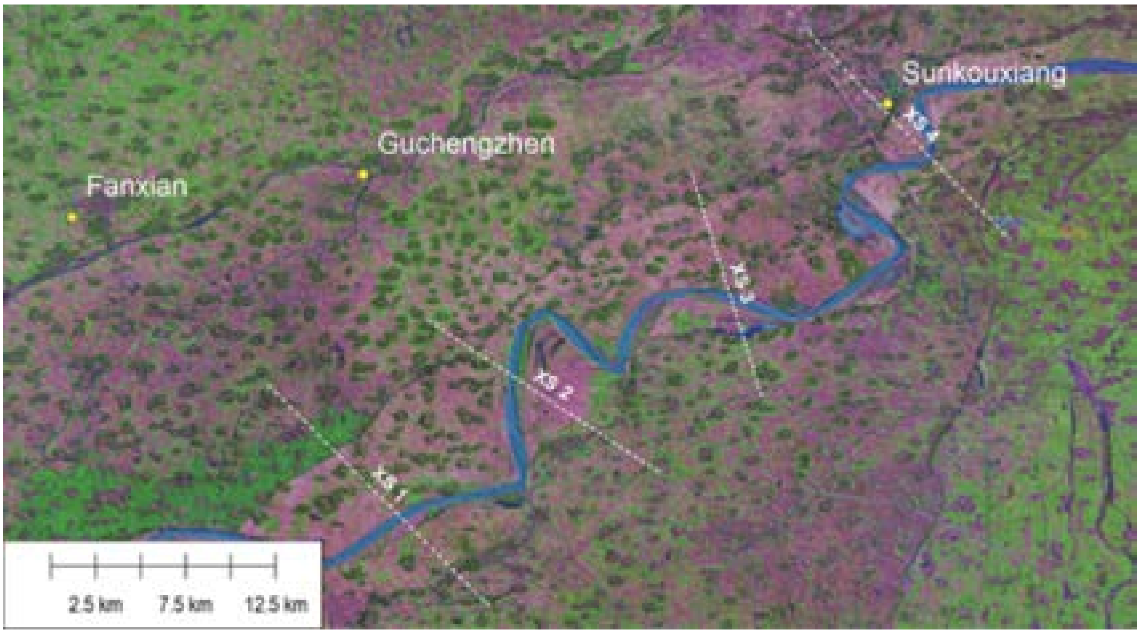
Note: The Kaifeng Liuyuankou Nature Reserve is located within this section of river. Locations of XS 1 to XS 4 are arbitrary. Landsat 7 true colour image (www.resmap.com) superimposed onto hill-shaded SRTM DEM (www2.jpl.nasa.gov/srtm/).

Figure 17. Middle section of reach 1 from Xiaolangdi to Gaocun near Kaifeng, cross-section morphology.



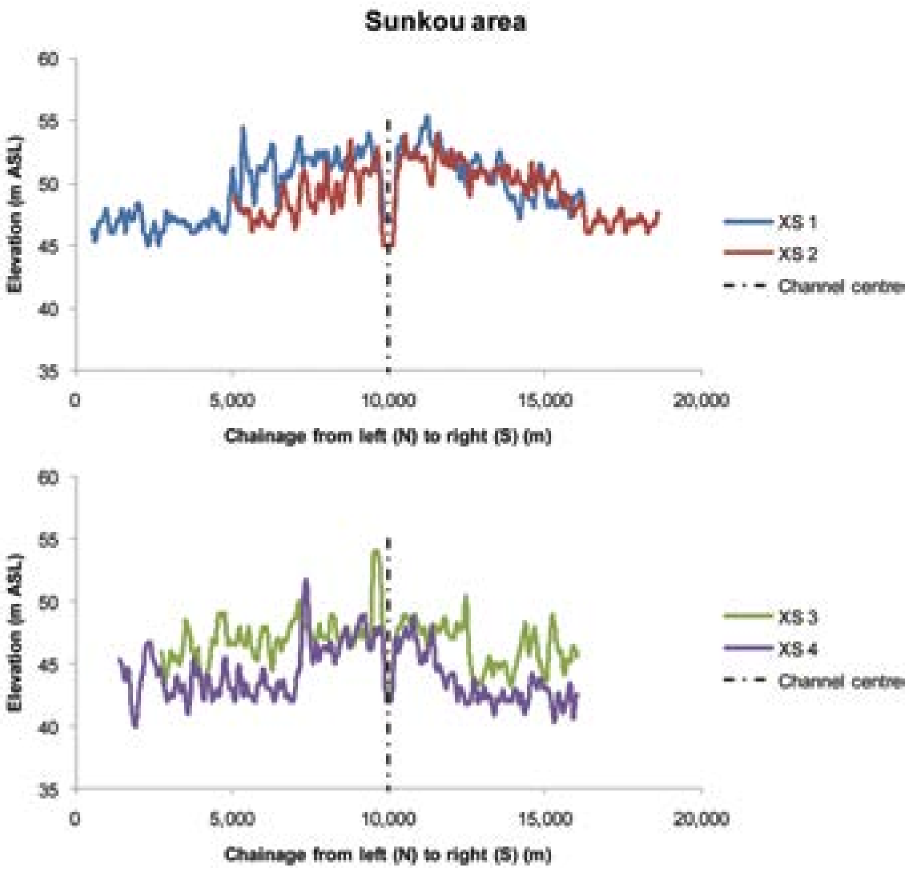
Note: For locations of Xs 1 to XS 4 see Figure 16. Cross-sections extracted from SRTM DEM (www2.jpl.nasa.gov/srtm/). Channel represented by water surface elevation.

Figure 18. Lower section of reach 2 from Gaocun to Taochengpu, near Sunkou.



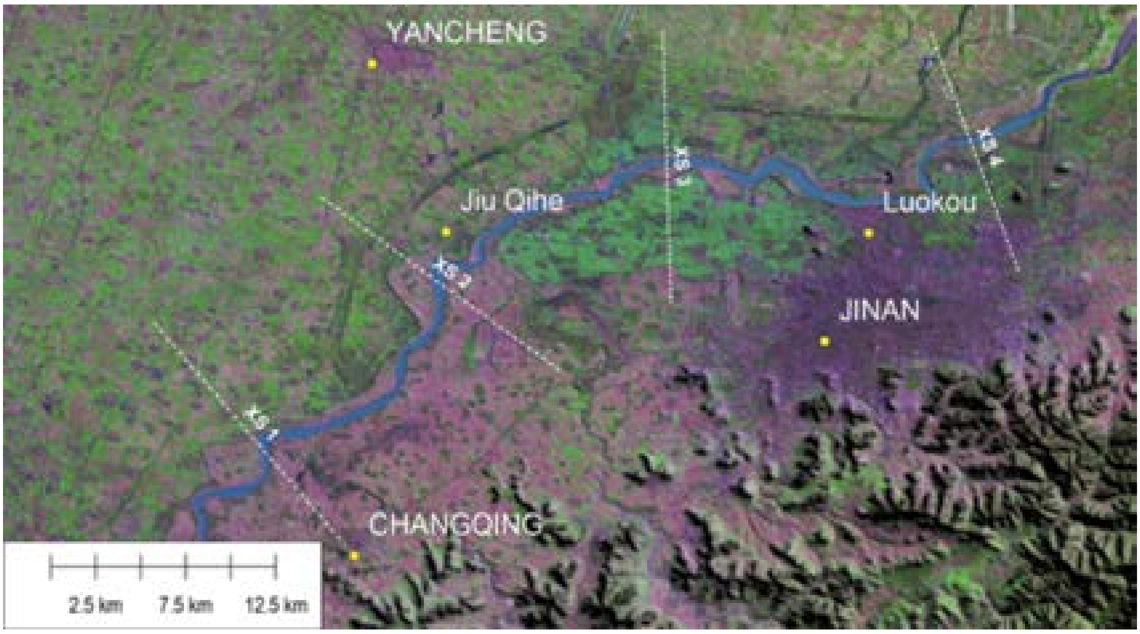
Note: Locations of XS 1 to XS 4 are arbitrary. Landsat 5 Mosaic image (www.resmap.com) superimposed onto hill-shaded SRTM DEM (www2.jpl.nasa.gov/srtm/).

Figure 19. Lower section of reach 2 from Gaocun to Taochengpu, near Sunkou, cross-section morphology.



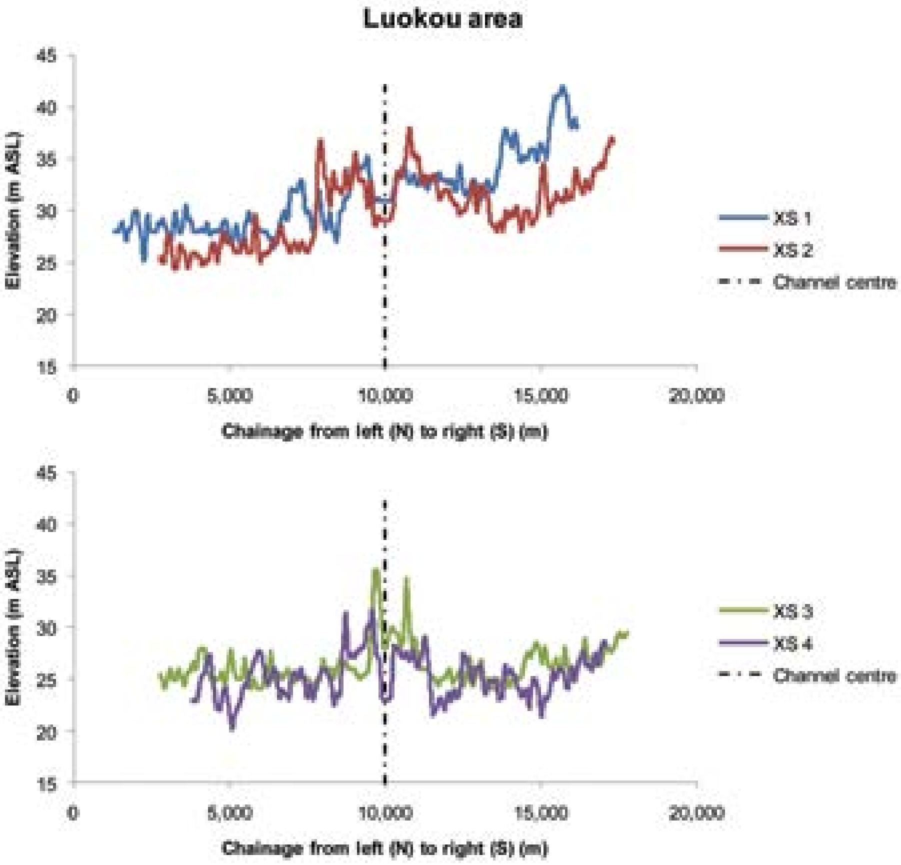
Note: For locations of XS 1 to XS 4 see Figure 18. Cross-sections extracted from SRTM DEM (www2.jpl.nasa.gov/srtm/). Channel represented by water surface elevation.

Figure 20. Middle section of reach 3 from Taochengpu to estuary, near Luokou.



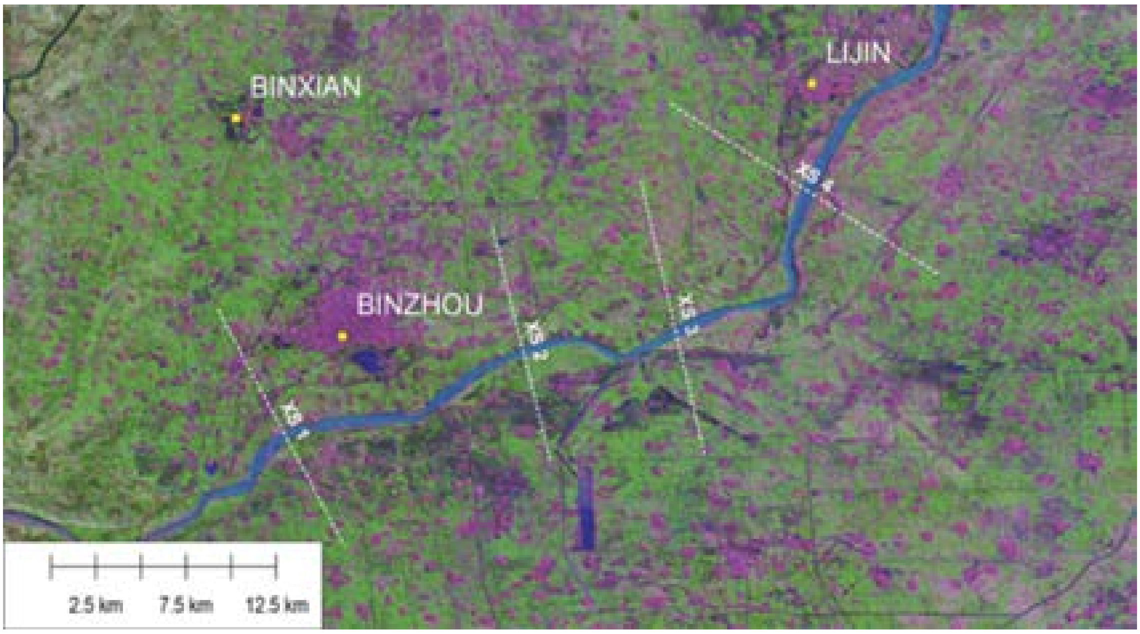
Note: Locations of XS 1 to XS 4 are arbitrary. Landsat 5 Mosaic image (www.resmap.com) superimposed onto hill-shaded SRTM DEM (www2.jpl.nasa.gov/srtm/).

Figure 21. Middle section of reach 3 from Taochengpu to estuary, near Luokou, cross-section morphology.



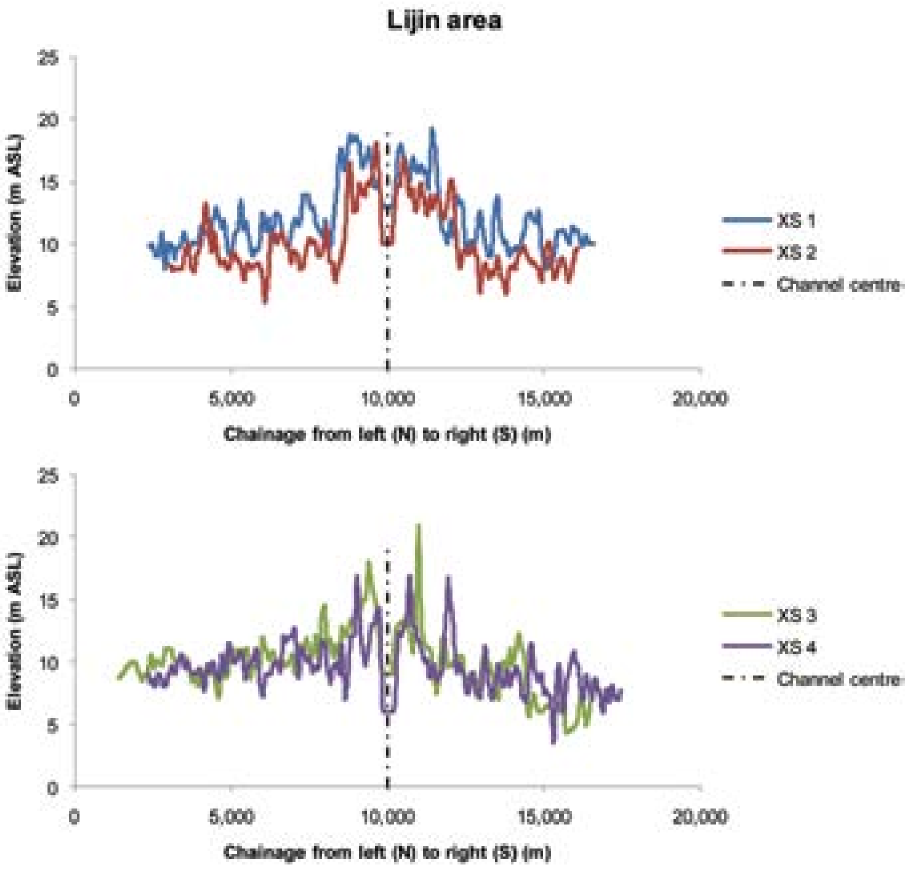
Note: For locations of XS 1 to XS 4 see Figure 18. Cross-sections extracted from SRTM DEM (www2.jpl.nasa.gov/srtm/). Channel represented by water surface elevation.

Figure 22. Lower section of reach 3 from Taochengpu to estuary, near Lijin.



Note: Locations of XS 1 to XS 4 are arbitrary. Landsat 5 Mosaic image (www.resmap.com) superimposed onto hill-shaded SRTM DEM (www2.jpl.nasa.gov/srtm/).

Figure 23. Lower section of reach 3 from Taochengpu to estuary, near Lijin, cross-section morphology.



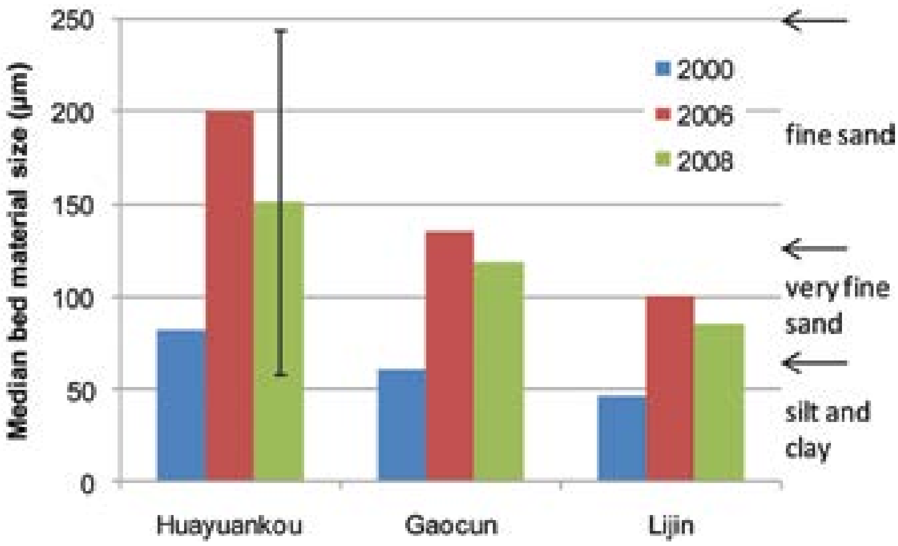
Note: For locations of XS 1 to XS 4 see Figure 22. Cross-sections extracted from SRTM DEM (www2.jpl.nasa.gov/srtm/). Channel represented by water surface elevation.

Wang H et al. (2010) plotted the median grainsize of suspended sediment in the Yellow River at a number of gauging stations. Over the period 1950 to 1999, between Huayuankou and Lijin the median grainsize was about 18–20 μm. In the period 2000–2006, after construction of the Xiaolangdi Dam and the associated annual water sediment release, the median sediment grain size at Huayuankou declined to about 16 μm. Further downstream at Gaucun, Aishan and Lijin, the median sediment grain size increased to 25–30 μm. The median size of the sediment leaving the Xiaolangdi Reservoir is only 6 μm, so the observed coarser grain size downstream of the dam is explained by scour and re-suspension of coarser sediment from the river bed and banks. Over the period 2000 to 2006, at least half of the suspended sediment load was sourced from the channel of the lower Yellow River (Wang H et al. 2010). Since the Xiaolangdi Dam began operating, most of the sediment transported in the lower river travels only a short distance from its source (the channel itself), so these re-suspended sediments are not sorted effectively, which explains the observed increase in the median grain size of suspended sediment delivered to the sea (Wang H et al. 2010).

The bed material of the lower Yellow River represents the coarser fraction of the suspended sediment. Chen et al. (2009) reported the median bed material particle size for Huayuankou, Gaocun and Lijin in 2000 and 2006; data for 2008 were supplied by YRCC (Figure 24). As with the suspended sediment, there was a coarsening of bed material grainsize following the operation of Xiaolangdi dam. Prior to Xiaolangdi the median bed material size was within the silt and clay range, but after the dam began operation the median particle size increased to very fine sand and fine sand (Figure 24). There is a suggestion in the data that the bed material may have become finer between 2006 and 2008, but these small differences might not be significant (this is not possible to test, as the raw data were available only for 2008). Chen et al. (2009) noted that the coarsening post-Xiaolangdi was responsible for increased flow resistance, and it reflected a reduced supply of fine material to the suspended load. Over time, the annual sediment-water transfer events have preferentially winnowed the finer material from the deposits on the bed of the river, effectively weakening the sediment transport efficiency.

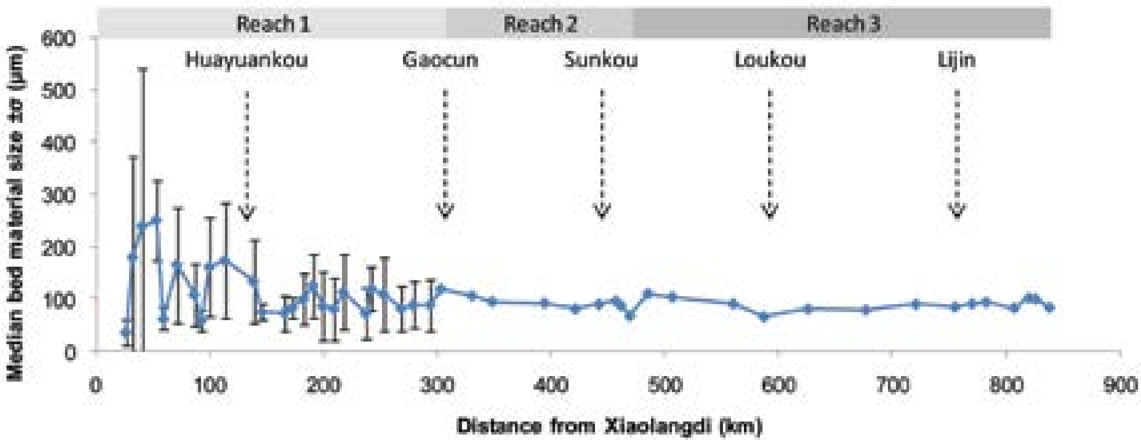
The downstream fining in bed material particle size apparent from Figure 24 is deceptive. In fact, the bed material is less well sorted close to Xiaolangdi, where the channel form is quite variable, so the median is variable and the standard deviation is high (Figure 25). Many of the sites sampled in reach 1, upstream of Gaocun, have a median particle size similar to that of sites downstream of Gaocun (Figure 25). Reach 2 and reach 3 are characterised by low variability in particle size between sampled sites. This reflects the relatively heterogeneous hydraulic conditions and channel morphology that prevails along these reaches of the river.

Figure 24. Median particle size of bed sediments in the lower Yellow River in 2000, 2006 and 2008.



Notes: Source of data: 2000 and 2006 data from Chen et al. (2009, Table 1) and 2008 data from YRCC. There was no sample from Huayuankou in 2008 so this value is based on data from nearby sites Qinchang (five samples) and Babao (six samples). For this site the median is the average of the medians of 11 samples, and the standard deviation is calculated from the medians of 11 samples. Gaocun and Lijin 2008 values are based on a single sample from each site.

Figure 25. Median particle size of bed sediments in the lower Yellow River in 2008.



Notes: Each reach 1 site value represents the average and standard deviation of the median sizes estimated for 5 or 6 samples taken across the river bed; reach 2 and 3 site data represent a single sample. Source of data: YRCC.

5.4 Groundwater

Having a perched morphology, and few tributaries, means that along most of its length the lower Yellow River is naturally a net 'losing' river – over a typical year the river loses surface water to groundwater. Groundwater contributes significantly to the total water resources available in the lower Yellow River. It is estimated that the average annual groundwater resource in the lower Yellow River is 2.5 × 10^9 m^3 (Xu et al. 2005). Water diverted from the river for irrigation also plays a great role in accelerating recharge to the local aquifer (Chen et al. 2002).

The Yellow River is the dominant source for the local aquifer, and the amount contributed from rainfall is close to zero for wells deeper than 30 m (Chen et al. 2002). The groundwater level is controlled by the river level (Xu, 1993). Si and Ye (2007) noted that groundwater levels under the dikes vary from 1 to 2 m below the surface. The level of the water table declines gradually to the south and to the north, controlling the direction of groundwater flow (Xu, 1993).

The cease to flow conditions that applied in the 1990s were found by Cao et al. (2008) to have had a significant effect on the pattern of variation in groundwater level. However, Cao et al. (2008) concluded that due to the large storage capacity of groundwater in the lower Yellow River this would have had little impact on the total resource available for exploitation.

While the majority of the lower Yellow River is a net 'losing' river, this is not the case for the non-perched section downstream of Xiaolangdi Dam to Gaocun (reach 1). Prior to regulation by Xiaolangdi Dam, the riparian floodplain wetlands of this reach were flooded annually for a reasonably long period. This resulted in groundwater recharge by vertical infiltration of water; the water table reached the surface, creating the wetland environment (Zhao et al. 2011; Xu et al. 2011). Regulation has meant that the floodplain is now never inundated, and groundwater recharge is by rainfall, irrigation, and brief annual periods of lateral infiltration during the water and sediment regulation events. The water table never reaches higher than within 0.5 m of the floodplain surface, and the groundwater regime is now dominated by drainage towards the river (Zhao et al. 2011; Xu et al. 2011).

5.5 Channel stability

A study of bank erosion on the braided reach of the lower Yellow River, from Huayuankou to Gaocun, was undertaken by Xia et al. (2008). This section of the river is known to be highly dynamic. Since operation of Xiaolangdi Reservoir the channel has undergone lateral main-channel widening with bed-level undercutting in some local reaches. As none of the controlled releases from the dam have overtopped the banks, the changes were associated solely with bank erosion. The reach between Huayuankou and Jiahetan was particularly dynamic because the morphology of the channel in this reach is less controlled by engineering works compared to reaches further downstream (Xia et al. 2008). Also, in this reach, Zhao et al. (2011) and Xu et al. (2011) noticed that rapid drawdown of the water and sediment regulation flow events resulted in the water table having a steep hydraulic gradient from the riparian area towards the river. This could induce seepage erosion and result in underground hollows within 50 m of the river's edge that threaten the stability of the bank.

The bank sediments comprise stratified layers of highly erodible material with low clay content (Xia et al. 2008). The upper layers had clay contents around 13 per cent (3–35 per cent range) and the lower layers had clay contents around 6 per cent (1–23 per cent range). The median particle size of the bank material ranged from 10 to 110 μm, while the bed material ranged in median size from 130 to 210 μm (which is consistent with other data, see Figure 24). Wu et al. (2005) pointed out that the bed material deposited in the vicinity of Huayuankou (they noted a median size of 90 μm) was close in diameter to the particle size of 100 - 200 μm that has the minimum critical shear stress for initiation of motion. Xia et al. (2008) found that the critical shear stress value of the bank material (0.1–0.3 N/m^2) was an order of magnitude less than that of the average near-bank flow shear stress (2.0 - 3.0 N/m^2), which explained the high erosion rates during high flow events. Compounding this, it was found that as the moisture content of the bank material increased (as would happen under inundation from high flows) the shear strength parameters and cohesion were drastically reduced (Xia et al. 2008).

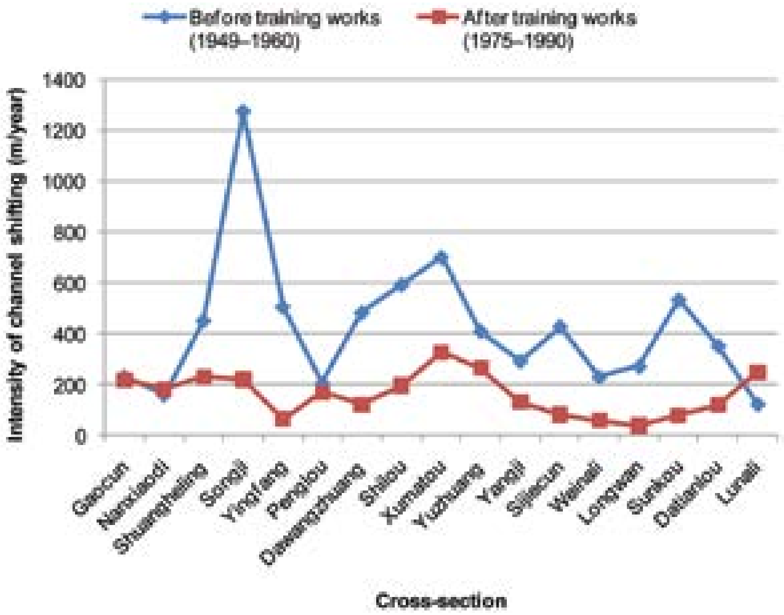
Early river training works on the lower Yellow River were intended mainly to protect the flood dikes from scour. Since 1950, efforts have been made to control the flow direction, with the ultimate aim of creating a stable, single thread meandering channel (Wu et al. 2005). The first phase of works was completed by 1958, with the stabilisation of the reach below Taochengpu in Shandong province. River training works were then undertaken on the reach from Gaocun to Taochengpu during the period 1965–1974. Experimental works began in 1973 on the braided reach from Tiexie to Gaocun, and more extensive works are planned for the future (Wu et al. 2005).

There are two basic types of training works on the lower Yellow River: works to protect the base of the dikes from scour, and works constructed along the banks mainly to guide the flow through the planned channel alignment. The engineering structures of the river training works consist of spur dikes, hardpoints, or short spurs, and revetments. As of 1997, over the full length of the lower Yellow River, more than 9000 spur dikes were constructed, and a total length of 647 km of channel was protected by works.

The effect of training works on the transitional Gaocun to Taochengpu reach was to dramatically stabilise the channel (Figure 26). Prior to works, the channel shifted at a rate of up to 1200 m per year, while after works the rate at observed cross-sections was mostly between 40 and 200 m per year (Figure 26). Also, the channel changed shape, becoming narrower and deeper. This led Wu et al. (2005) to conclude that the training works had essentially transformed the reach from a transitional to a confined meandering planform.

Examination of the degree of braiding in the three selected sections with river training works within the Tiexie to Gaocun reach revealed that a marked stabilisation of channel position was achieved (Wu et al. 2005). Liang and Ding (2004) also documented changes to the channel, in the reach from Mengjen to Kaifeng. They compared the channel position using Landsat images from 1987 and 2002. The river channel was observed to become narrower, and its multi-channel character (degree of braiding) diminished. Liang and Ding (2004) put this down to the combined effects of regulation from Sanmenxia Dam, and river training works. They reported that the active width of the floodplain across which this section of the river regularly migrated varied through time from an average of 5–7 km pre-Sanmenxia Dam, 3.36 km in the period 1964–1972, 2.46 km in the period 1981–1988, and 1.92 km in the period 1987–2002.

Figure 26. Rate of shifting of main flow paths at cross-sections in the reach from Gaocun to Taochengpu (reach 2) before and after river training works were implemented.

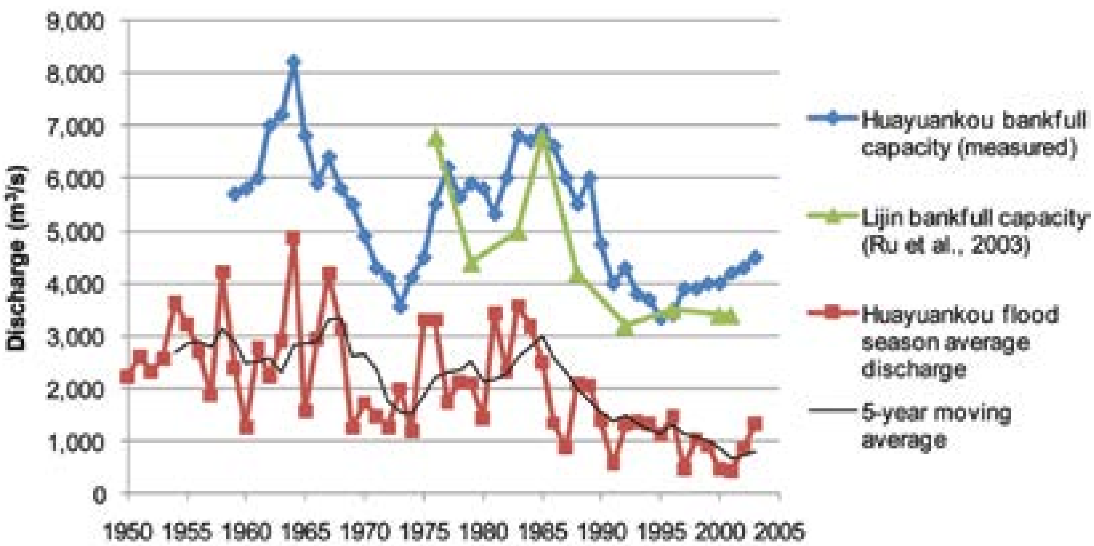


Source: Wu et al. (2005).

5.6 Sediment transport and channel capacity

The bankfull capacity of the lower Yellow River channel has varied significantly over time (Figure 27). Wu et al. (2008) measured, for each year from 1950 to 2003, the morphological bankfull stage from cross-sections on the lower Yellow River surveyed near gauging stations, and then determined the bankfull discharge from the gauge rating curves (Figure 27). The bankfull capacity at Lijin, as reported by Ru et al. (2003), followed the same pattern as that observed by Wu et al. (2008a) at Huayuankou (Figure 27). The adjustment of the channel occurs mainly under high flow conditions, and there was clearly a relationship between the temporal pattern of bankfull discharge and flood period (July to October) discharge (Figure 27). Wu et al. (2008a) found that each adjustment of bankfull capacity depends on the initial morphological conditions, which reflected the conditions that prevailed in the preceding 5 to 6 years. Therefore the bankfull channel dimensions at any time are a result of the accumulative effect of several consecutive years discharge and sediment load conditions (Wu et al. 2008a).

Figure 27. Measured bankfull discharge at Huayankou, mean daily discharge in the flood season (July to October), and moving average of discharge, from 1950–2003.



Source: Wu et al. (2008a). For comparison, bankfull capacity estimated by Ru et al. (2003) for Lijin is also shown.

The channel sediment delivery ratio (SDR) is defined as the ratio of sediment outflow to the sum of sediment inflow for a given river reach. The higher this index, the more efficient is the river reach for sediment transport. Xu (2003) plotted the SDR against the total flood event water volume (Q_w) and the flood event peak water discharge (Q_{max}). Although the points were scattered, peak SDR could be identified at Q_w = 18 × 10^8 m^3 and at Q_{max} = 4000 m^3/s. Also, Xu (2003) found that that the deeper and narrower the channel shape, the higher the SDR is at high suspended concentrations.

Hu and Guo (2004) reported that the lower Yellow River channel will remain stable under the conditions of discharge 2600 m^3/s and sediment concentration 20 kg/m^3 (Note: a discharge of 2600 m^3/s was used in the flood release from Xiaolangdi Reservoir in July, 2002; see Ni et al. 2004 and Yu, 2006).

The model of Ni et al. (2004) predicted that sediment concentration less than 20 kg/m^3 was favourable for sediment flushing by controlled flood release. For a sediment concentration of 20 kg/m^3 the efficient discharges for sediment control in reaches of the lower Yellow River downstream of Huayuankou ranged from 2390 to 2900 m^3/s (from Xiaolangdo Reservoir). For the reach from Sanmenxia to Huayunakou the efficient discharge was 4375 m^3/s (Ni et al. 2004). In earlier work Ni et al. (2002) and Ni and Qian (2002) reported that the critical discharges for efficient transport of sediment in the flood season were 1972.3 m^3/s for Sanmenxia-Huayuankou reach, 2042.1 m^3/s for Huayuankou-Gaocun reach, 2321.9 m^3/s for Gaucun-Aishan reach and 2684.4 m^3/s for Aishan-Lijin reach. In the non-flood season the estimated critical discharges were 835.4 m3/s for Sanmenxia-Huayuankou reach, 831.5 m^3/s for Huayuankou-Gaocun reach, 756.3 m^3/s for Gaucun-Aishan reach and 667.3 m^3/s for Aishan-Lijin reach.

Liu et al. (2006) reported the results of various research efforts concerning sediment transport in the lower Yellow River. Based on the observed data series of 168 floods from 1974 to 1990, it was proposed by Yue (1996) that the most efficient discharge and sediment concentration was 3500 m^3/s and 75 kg/m^3 respectively. This finding agreed with the observation that the velocity at Gaocun did not appreciably increase beyond around 3000 m^3/s (Liu et al 2006). Other observations of scouring capacity found that there was no increase beyond around 3500 m^3/s (Liu et al 2006). These flow levels were close to bankfull capacity of the channel. Liu et al. (2006) set the objective for bankfull capacity at 4000 m^3/s, and because of the observed relationship between sediment transport efficiency and bankfull discharge, set this as the target discharge for the annual WSDR event for the lower Yellow River.

Zhang et al. (2006) considered that the optimum sediment concentration for sediment transport was 60 kg/m^3. Based on this figure, and an estimate of the volume of sediment required to be scoured, Zhang et al. (2006) estimated that the annual water demand for sediment transportation in the lower section of the Yellow River was about 17.6 × 10^9 m^3. This figure is based on an assumed sediment transport rate of 16 m^3/tonne, as estimated by Qi and Li (1994), and annual sediment load of 1.3 × 10^9 tonnes, and an allowable annual sedimentation of 0.2 × 10^9 tonnes in the lower Yellow River channel.

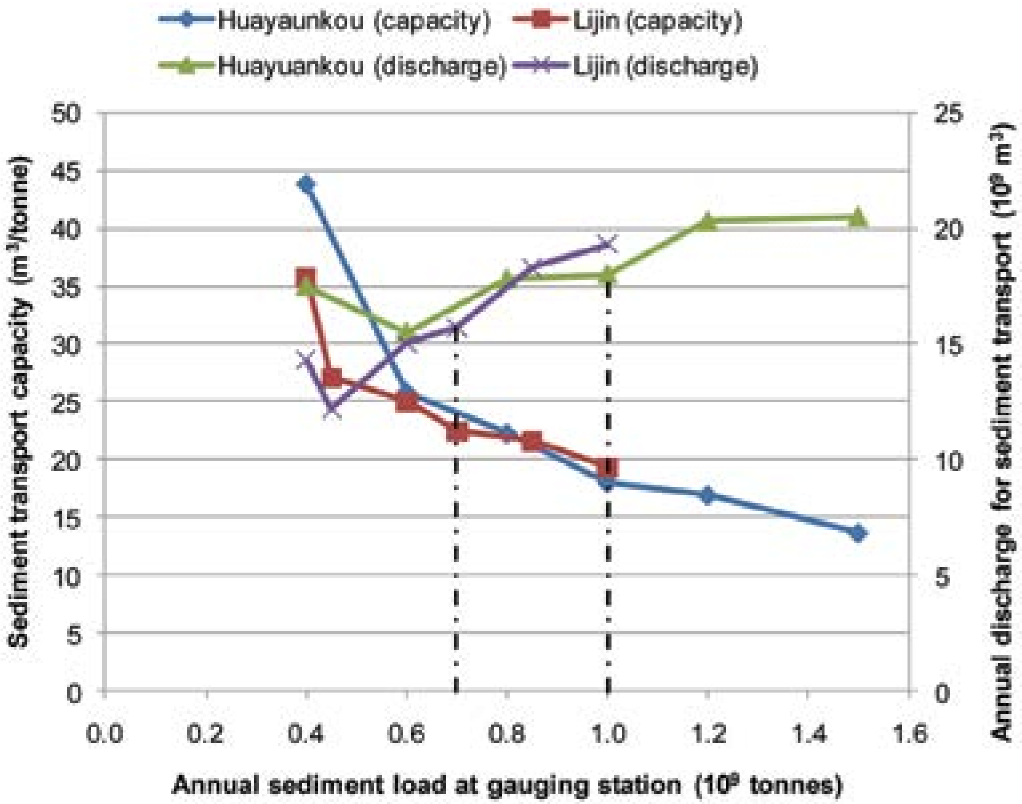
Yang ZF et al. (2009) estimated the volume of water required annually for scouring sediment from the Yellow River, based on the volume of sediment stored in the channel and the sediment transport capacity of the river. They obtained a figure of 15–20 × 10^9 m^3 for the flood season and 10–15 × 10^9 m^3 for the non-flood season.

Cui et al. (2009) cited research by Cui, S and Song, S of Haihe River Water Conservancy Commission (http://www.hwcc.gov.cn/pub/hwcc/index.html) that estimated the required annual discharge for sediment transport below Sanmenxia gorge was 15 × 109 m3.

Giordano et al. (2004) reported that 1 × 10^9 tonnes of sediment is believed to enter the lower Yellow River each year (see also Wang et al. 2004). Of these, 0.4 × 10^9 tonnes are calculated to be captured by two large reservoirs and various irrigation diversions, 0.1 × 10^9 tonnes are believed to settle within the lower reach, and an additional 0.1 × 10^9 tonnes are flushed to the sea through dry-season minimum flow. To flush the remaining 0.4 × 10^9 tonnes, an environmental water requirement of 14 × 10^9 m^3 is required. This figure is based on an assumed sediment transport rate of 35 m^3/tonne, which is double the estimate used by Zhang et al. (2006).

Setting recovery of channel capacity as the objective, the work of Shen et al. (2006) resulted in relationships between sediment transport capacity and annual discharge required for sediment transport as functions of the annual sediment load in the lower Yellow River (Figure 28). These relationships indicate that sediment transport capacity varies depending on the load of sediment to be transported, and this impacts the estimate of annual discharge required to transport that sediment load (Figure 28). It is interesting to note that the other estimates made in the literature (reported above) are generally consistent with these relationships. It can be seen from Figure 28 that transport of the mean annual sediment load of 1 × 10^9 tonnes at Huayuankou (equivalent to 0.7 × 10^9 tonnes at Lijin due to deposition) requires just over 15 × 10^9 m^3 of water at Lijin.

Figure 28. Relationships between sediment transport capacity and annual discharge required for sediment transport as functions of the annual sediment load in the lower Yellow River.



The dashed line is drawn at the often-quoted mean sediment load of the river. Source Shen et al. (2006, Table 1).

5.7 Delta geomorphology

The Yellow River delta is geomorphologically dynamic, so its area has varied through time. In 2006 Chu et al. (2006) reported that it occupied an area of 5129 km^2 (Chu et al. 2006). Hu and Cao (2003) developed a sediment budget for the delta. About three per cent of the sediment load that passes Lijin is deposited in the river course, about 50 per cent is deposited near the river mouth, and the rest discharges into the Bohai. The delta sediment is composed of easily eroded silt and clay that is subsiding due to compaction processes (Chu et al. 2006).

Chu et al. (2006) developed a conceptual model of delta development for the Yellow River. When the river shifts its course, a new promontory at the river mouth develops quickly and the coastline begins to advance seaward. After high initial rates, the net accretion rate slows, and sometimes erosion occurs. The modern delta developed since 1855, and over that time it has shifted course more than 50 times, with eight to twelve of them considered to be major events (Chu et al. 2006; Fan et al. 2006). In 1976 the river course was artificially relocated from the Diaokou Promontory to the Qingshuigou Promontory, and it was again artificially diverted to the current Qing 8 Promontory (Chahe distributary) in 1996. This diversion shortened the length of river channel by 16 km and steepened the riverbed gradient by 2.89 times, resulting in upstream scouring and a fall in the water level in the mouth channel (Fan and Huang 2005). The general pattern of accretion and erosion of the entire modern Yellow River sub-aerial delta was divided by Chu et al. (2006) into three stages: rapid accretion stage (1976–1984), accretion–erosion adjustment stage (1985–1995), and slow erosion stage (1996–present).

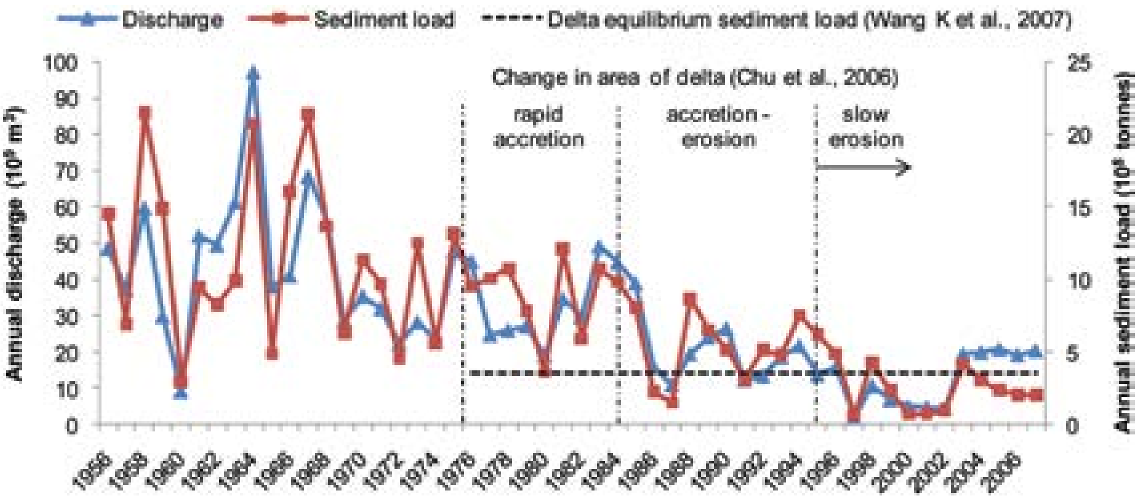
Chu et al. (2006) found that the cumulative area (A) of increase over the entire sub-aerial delta and the cumulative Yellow River sediment discharge (Q_{sed}) at Lijin (1976-2000) were closely related ($A = 1.7223 \times Q_{sed} + 51.3$; R^2=0.75, n =19, A in km^2, Q_{sed} in 10^8 tonnes). Similarly, Fan et al. (2006) found that the distance of the mouth-bar crest seaward from Xihekou (D) and the cumulative Yellow River sediment discharge (Q_{sed}) (1984-1995) were closely related ($D = 0.2217 \times Q_{sed} + 39.251$; R^2=0.97, n = 10, D in km, Q_{sed} in 10^8 tonnes).

There were two main phases of mouth bar development since the 1970s. After 1990 the rate of mouth-bar progradation dropped, related to the significantly reduced runoff and sediment load to the estuary (Fan et al. 2006). A similar pattern was observed for tidal flats in the delta (Fan and Huang 2004). Ru et al. (2003) noted that the bankfull discharge capacity of the delta channel at Shibagongli decreased from 1976 to 1979. It enlarged to 5,000 m^3/s in 1985 due to scour by floods in the period 1980-1985, after which it decreased to about 3,000 m^3/s in 2001. Since 2002 (post-Xiaolangdi Dam) implementation of the WSDR has reversed this trend and increased the rate of delta progradation (Huang S et al. 2007).

The average sediment accumulation rate in the Qingshuigou delta lobe for 1976–1992 was about 1.2 m/year, most of which was deposited in the river mouth area (Fan et al. 2006). The active river-mouth bar prograded at a rate of 1–4 km/year and the delta lobe extended at a rate of 20–25 km^2/year (Fan et al. 2006). Although the river-mouth bar is not large, it can exert a strong influence on the hydraulics of the river upstream. Sedimentation on the bar can cause high rates of sedimentation in the river channel upstream, thus increasing flood risk and risk of channel avulsion (Fan et al. 2006).

Wang K et al. (2007) estimated that an annual average sediment load of 3.45 × 10^8 tonnes at Lijin would maintain (at equilibrium) the delta coastline of the Yellow River estuary. It follows that progradation of the coastline, which supports rapid plant succession – a defining ecological characteristic of the delta –requires loads higher than this. A plot of the time series of annual sediment load, when compared with the observations of delta area change by Chu et al. (2006), supports the estimate of equilibrium sediment load by Wang K et al. (2007) (Figure 29).

Figure 29. Annual sediment load and discharge at Lijin (for calendar years) for the period 1956-2007, showing phases of delta change.



Notes: The phases of delta channel are as identified by Chu et al. (2006) and the sediment load threshold required for equilibrium of delta area identified by Wang K et al. (2007). In 1976 the river course was artificially relocated from the Diaokou Promontory to the (current location) Qingshuigou Promontory. Source: sediment load data from Miao et al. (2010) and discharge data from YRCC.

When rivers enter the sea, the density of the freshwater-sediment mixture is usually much too low to offset the density contrasts due to salinity and temperature. The suspended sediment from the light surface layers gradually but progressively falls to the sea floor (Wright et al. 1986). In contrast, the extremely high-suspended sediment concentrations that can issue from the mouth of the Yellow River are sufficient to favour hyperpycnal plumes (underflows) (Wright et al 1986). One of the features of hyperpycnal plumes is the higher turbidity river water remains relatively close to the river mouth. On the Bohai, Wright et al. (1986) observed surface suspended solids concentrations less than 10 mg/L beyond 20 km from the Yellow River mouth, when at the mouth the concentration exceeded 1000 mg/L. This explains why the water of the Bohai is exceptionally clear, even in relatively close proximity of the mouth of the Yellow River. Hyperpycnal plumes produce precipitous deposition near their source, which explains why about 90 per cent or more of the sediment discharged by the Yellow River remains within a few kilometres of the mouth, to constitute rapidly prograding delta lobes (Wright et al. 1986).

Wang et al. (2010) calculated that for the Yellow River delta, the critical suspended sediment concentration to form a hyperpycnal plume that would descend to the bottom is 35 kg/m^3. During the period 1950–1999, ~ 65 per cent of the suspended sediment load at Lijin gauging station was transported to the sea during the flood season (July–September), with mean suspended sediment concentration exceeding 35 kg/m^3. These conditions were favourable for the formation of a hyperpycnal plume. However, over the period 2000–2006 only ~ 35 per cent of suspended sediment was delivered to the sea during the flood season (July–September), and the mean sediment concentration during the flood season

(<10 kg/m^3) was much lower than the critical threshold concentration required to produce a hyperpycnal plume (Wang et al. 2010). The reduction was largely the result of sediment and high flow season flows being retained within Xiaolangdi reservoir, which became operational in late 1999.

During 1950–1999, hyperpycnal events (defined by suspended sediment concentration >35 kg/m^3) occurred on average 33 days each year and contributed ~ 52 per cent of the annual sediment delivery to the sea, whereas during 2000 – 2006, hyperpycnal events occurred on average only 3 days each year and delivered ~ 12 per cent of the annual sediment load to the sea (Wang et al. 2010). Despite this, the delta continued to prograde between 1999 and 2009. Although sediment load to the delta over this period was low compared to historical levels, the sediment particle size increased (because much of it was sourced from scour of the river channel itself), and Wang et al. (2010) explained delta growth in terms of rapid deposition of coarse sediments directly off the mouth. Wang et al. (2010) noted the importance of retaining hyperpycnal events at the river mouth, to maintain biogeochemic cycles in the estuary and to sustain the pattern of delta building.

5.8 Catchment sediment load

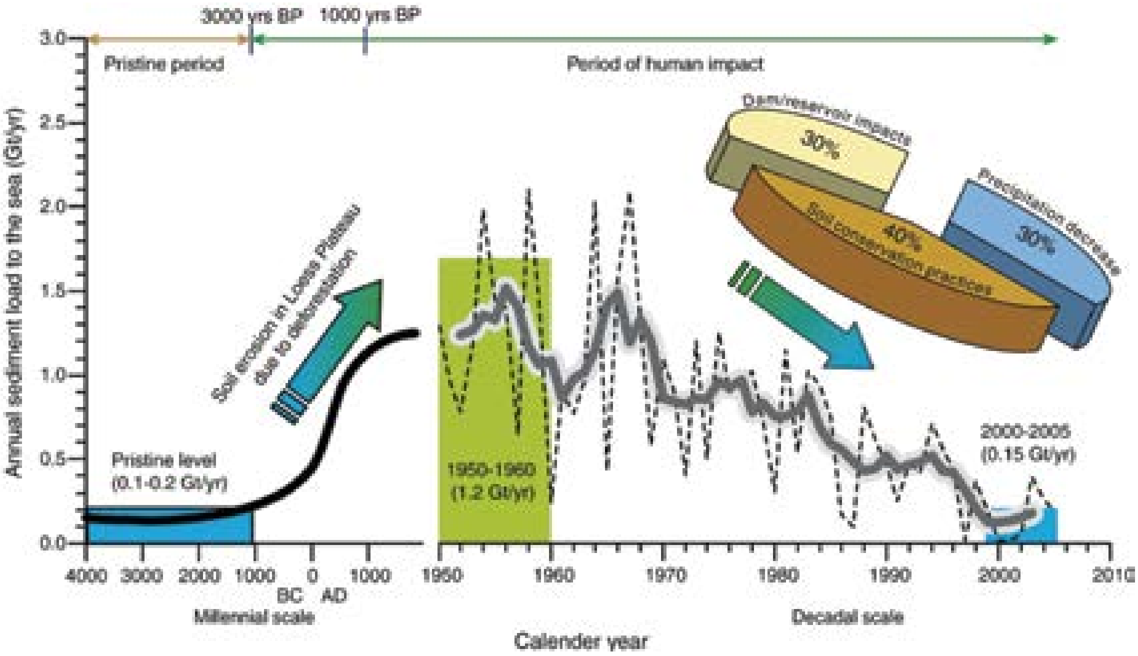
Wang et al. (2007) compiled data from various sources to demonstrate that by the late 1990s the sediment load of the Yellow River to the sea had fallen back to the pristine levels of 3000 years ago (Figure 30). The increase in sediment loads from around 1000 years ago until 1950 was driven by increasing population and associated deforestation, although this was superimposed on a trend of increasing sediment loads associated with Quaternary tectonic uplift (Shi and Shao 2000). In the early part of the last 1000 years, although the sediment load was high, much of it deposited on the floodplain (the North China Plain) because floods freely spilled from the channnel. In the period of high sediment load in the 1950s and 1960s the river was confined within levees, so most of the sediment reached the sea. Since 1855, when the river took its present course, up until the 1990s, the high sediment loads to the sea built a rapidly prograding mega-delta.

To reduce the sediment load of the Yellow River, soil conservation measures have been implemented across the Loess Plateau region since the 1950s (Rustomji et al. 2008). He et al. (2006) found that modern rates of soil erosion on the Loess Plateau are around four times greater than occurred in the geological past, and attributed a recent 25 per cent reduction in sediment loads to implementation of soil and water conservation measures. However, it has been noted that the reduction in sediment load was coincident with a reduction in discharge, which could explain the reduction, as sediment load is a product of sediment concentration and discharge (Zhang et al. 2008). Zhao et al. (1992) attributed the observed change in sediment load of a sub-catchment of the Yellow River equally to sediment yield reduction and discharge reduction. Rustomji et al. (2008) found statistically significant reductions in both sediment load and sediment concentration in catchments in the Coarse Sandy Hilly Catchments (CSHC) area of the Loess Plateau, which confirmed the effectiveness of soil conservation measures in reducing sediment loads. In nine of the eleven catchments studied by Rustomji et al. (2008), soil conservation measures accounted for 64–89 per cent of the reduction in sediment yields. The change point in reduction of sediment yield occurred between 1971 and 1982 for nine of the eleven catchments. The study of Rustomji et al. (2008) did not investigate the role of large dams in reducing the sediment load of the Yellow River through trapping of sediment. Wang et al. (2007) attributed 30 per cent of the reduction in sediment load to the Yellow River Delta since 1950 to this process.

Wang et al. (2007) were of the view that the main causes of the decline in sediment load since the 1960s (Figure 30) will continue to apply into the future, so they predicted that decline of the mega-delta was inevitable, due to marine erosion outpacing fluvial deposition. Given this, it may be futile to set as a management target ecosystem characteristics that derive from a rapidly prograding delta.[15]

15 The major environmental values for which the site was deserving of Ramsar listing appear to at least partly hinge on rapid delta progradation. For example Chen et al. (2007, p. 2) stated that, '*Since it is a newly-developed wetland ecosystem, the 393 plant species of the Yellow River Delta Nature Reserve is of great scientific and conservation significance… There exist vast even mudflat areas in the Yellow River Nature Reserve, which provide an excellent habitat for waterfowl*'.

Figure 30. Past and present sediment load discharged from the Yellow River to the Bohai.



Source: Wang et al. (2007).

5.9 Geomorphologic flow objectives

The geomorphologic-related objectives for managing the lower Yellow River are based on the wealth of existing research and experience in the river. The fundamental reason for managing the geomorgological aspects of the river is to assist with management of flood risk. Risk is lowered by maximising the channel capacity, deepening the channel bed (i.e. achieving a lower width/depth ratio), and increasing channel bank stability (limiting the channel as a sediment source). Flood risk is also managed by providing storage space in reservoirs during the flood season.

There are secondary ecological-related reasons for managing the geomorphologic aspects of the river. The process of scour, transport and deposition of sediment creates diversity of habitats. In geomorphologically dynamic environments, erosion and deposition processes will locally destroy older vegetation, and create new surfaces for colonisation by pioneer species (Richards et al. 2002). As noted by Richards et al. (2002), there is strong evidence from river environments that physical habitat heterogeneity plays a crucial role in maintaining biodiversity. Similarly, Florsheim et al. (2008) made a case for bank erosion as a desirable attribute of rivers. While dynamic channel morphology may be associated with biodiversity, in the lower Yellow river, channel stability is preferred for flood risk minimisation, although bed scour is viewed favourably because this increases channel capacity.

The over-riding imperative to avoid flooding of the lower Yellow River has meant stabilisation of the channel for much of its length. Only in the reach from Xiaolangdi to Gaocun is the channel not fully constrained by rock revetments and groynes, but the intention is to expand river training works further into this reach in the future. At present, reach 1, from Xiaolangdi to Gaocun has significantly higher morphological diversity than reaches 2 and 3, and it is also more morphologically dynamic. Reach 1 has the widest active floodplain and contains three important river-connected wetlands.

The ecological character of the delta relies on morphological change, with plant succession being driven by rapid seaward progradation of the delta.

Maintenance of geomorphological processes requires achievement of a number of objectives (Table 13). These geomorphic-based objectives were interpreted in terms hydrological objectives (Table 13).

Table 13. Geomorphologic-based objectives and flow requirements.

No.	Objective	Flow component	Hydrologic criteria	Mean annual frequency/ duration	Inter-annual frequency	Timing	Reach	Reference
G1	Scour and deposition processes to maintain dynamic and diverse habitats in the channel and connected floodplains	Bankfull	2600–4000 m^3/s	≥ 1 per year / ≥ 1 day* duration	≥4 in 5 years	Jun–Sep	Reach 1	Richards et al. (2002)
G2	Maintain channel capacity at 4,000 m^3/s	Bankfull	2600–4000 m^3/s	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun–Sep	All reaches	Liu et al. (2006)
G3	Seaward progradation of the delta	Bankfull	Sediment load >3.45×10^8 tonnes at Lijin; event mean sediment concentration ≥ 35 kg/m^3	≥ 1 per year	≥4 in 5 years	Jun–Sep	Reach 4	Wang K et al. (2007); Wang et al. (2010)
G4	Flow into delta wetland channels to maintain channel form (and also provide freshwater and nutrients to the delta wetlands)	Bankfull	>3,000 m^3/s to allow gravity flow	≥ 1 per year / ≥ 10 days* days duration (or as required)	≥4 in 5 years	Jun–Sep	Reach 4	Jiang Xiaohui (YRCC, pers. comm., November 2010)

* Based on expert opinion; refinement of this criterion will require investigation.

Chapter 6. Hydrology

6.1 River regulation

Although reservoir construction began in the Yellow River basin several thousand years ago, most of the large dams were built in the second half of the 20th century. In that period more than 3,000 reservoirs were constructed in the basin. Following completion of Xiaolangdi Dam in 1999 the total storage capacity in the catchment reached around 70 × 10^9 m^3 (Cai and Rosegrant 2004; Xu et al. 2005; Wang et al. 2006; Miao et al. 2010). There are 24 reservoirs with total storage capacities exceeding 0.10 × 10^9 m^3 (Wang et al. 2006).

Of the total storage capacity, some is unusable, known as dead storage. Flood storage capacity is the capacity available to control large floods in emergency situations by drawing down the dam level. Flood storage capacity is an indicator of the potential impact of a dam on attenuation of high flood peaks. Active storage capacity is the volume that is available for regulating the flow most of the time, and this is an indicator of the potential impact of a dam on important environmental flow components, including baseflows, flow pulses and small to medium-size floods.

The four largest and most hydrologically influential reservoirs on the mainstem of the Yellow River are the Sanmenxia, Liujiaxia, Longyangxia and Xiaolangdi reservoirs (Fuggle et al. 2000; Wang et al. 2006). Sanmenxia and Xiaolangdi are located on the downstream end of the middle Yellow River basin between Tongguan and Zhengzhou, and Longyangxia and Liujiaxia are located in the upper basin, upstream of Lanzhou.

The construction of Sanmenxia Dam began in April 1957 and it was operational by September 1960 (Wang et al. 2005). Sanmenxia was built as a multipurpose project for flood control, hydropower, irrigation, navigation, and ice jam control. The drainage area above the dam amounts to 688,400 km^2, which is 94.3 per cent of the total drainage area of the Yellow River. During the first 18 months of operation, 93 per cent of the incoming sediment was trapped in the reservoir, causing a loss of 17 per cent of its storage capacity (Wang et al. 2005). To mitigate the sedimentation problems, the mode of operation of the dam was changed in March 1962 to detain only floodwater in flood seasons and to sluice sediment with the largest possible discharges available at the time. The sluicing capacity was considered inadequate, and an upgraded system was put into operation in July 1966. The mode of operation was changed again, beginning in November 1973, to store relatively clear water in non-flood seasons (November–June) and discharge turbid water in flood seasons (July–October). In this mode the reservoir was operated at a high level in the non-flood season to store water for irrigation and hydropower generation, and operated at a low storage level during flood season. In times of flood discharge exceeding 2,500 m^3/s all the outlets were opened to sluice sediment (Chen and Liu 1988; Wang et al. 2005). In the original design, the storage capacity of Sanmenxia was 647 × 10^8 m^3 at a water elevation of 360 m (Wang et al. 2005). However, because of sedimentation, and changes to the normal operating elevation, the dam's total capacity is most often reported as 96.4 × 10^8 m^3 (e.g. Xu et al. 2005; Wang et al. 2006; Yang et al. 2008), although Ma et al. (2010) quoted a volume of 162 × 10^8 m^3 after modifications in the early 1970s. Active storage volume is currently 11.81 × 10^8 m^3 (Jin Shuangyan, Institute of Yellow River Hydrology and Water Resources, Hydrology Bureau, YRCC, pers. comm. October 2010). Thus, the current active storage volume is only a fraction of the original total storage volume.

Xiaolangdi Dam, built between 1994 and October 1999, is located 130 km downstream of Sanmenxia Dam and 128 km upstream of Huayuankou gauge. The drainage area above the dam amounts to 694,000 km^2, which is 95.1 per cent of the total drainage area of the Yellow River. The 154 m high dam was built as a multipurpose project for flood control, ice-jam prevention, sediment control, power generation, flow regulation for irrigation, and domestic and industrial water supply (Fuggle et al. 20000). Although it has other purposes, Xaiolangdi Dam was built mainly for flood protection, being designed to increase the level of flood protection in downstream areas from once in 60 years to once in 1,000 years (Ludwig et al. 1995), although Fuggle et al. (2000) cited a level of protection of once in 10,000 years. Xiaolangdi reservoir was designed to operate in harmony with other upstream reservoirs for water and sediment control (Guxian, Luhun on the Liyuohe system, and Sanmenxia) (Fuggle et al. 2000). A complex system of 15 large tunnels with an underground powerhouse makes it possible to flush sediments by creating controlled floods in the main river channel (Power-Technology.com, 2011). The power plant's capacity is 1,836 MW, generating 5.1 × 10^9 kWh of electricity per year (Power-Technology.com, 2011). The total storage capacity of Xiaolangdi Dam is usually given as 126.5 × 10^8 m^3 (Xu et al. 2005; Yang et al. 2008; Ma et al. 2010). The active/flood storage capacity of Xiaolangdi was given as 40.5 × 10^8 m^3 by Yang et al. (2008) and Wang et al. (2005). However, the current active storage volume supplied by YRCC (Jin Shuangyan, Institute of Yellow River Hydrology and Water Resources, Hydrology Bureau, YRCC, pers. comm., October 2010) is 51 × 10^8 m, which is also the figure given by Xu et al. (2005) and Ludwig et al. (1995).

Longyangxia and Liujiaxia Dams are the two large upper-basin multi-purpose dams situated on the main stem of the Yellow River. These dams provide gravity irrigation mainly along the Huangshui River between Xining and Lanzhou (Ma et al. 2010). As such, they are usually operated to store water in the high flow season and release it during the irrigation season. Liujiaxia Dam was built between 1958 and October 1968. The drainage area above the dam amounts to 181,800 km^2, which is 24.9 per cent of the total drainage area of the Yellow River. The dam's total capacity is variously given as 60.9 × 10^8 m^3 (Ma et al. 2010) and 57 × 10^8 m^3 (Xu et al. 2005; Wang et al. 2006). The active storage volume is 41.5 × 10^8 (Jin Shuangyan, Institute of Yellow River Hydrology and Water Resources, Hydrology Bureau, YRCC, pers. comm., October 2010; Xu et al. 2005).

Longyangxia Dam, located upstream of Liujiaxia Dam, is by far the largest dam in the basin in terms of active storage volume. It was built between 1978 and October 1986. The drainage area above the dam amounts to 131,420 km^2, which is 18.0 per cent of the total drainage area of the Yellow River. The dam's total capacity is variously given as 268 × 10^8 m^3 (YRCC), 247 × 10^8 m^3 (Xu et al. 2005) and 276 × 10^8 m^3 (Fuggle et al. 2000; Wang et al 2006). The active storage volume is 193.6 × 10^8 m^3 (Jin Shuangyan, Institute of Yellow River Hydrology and Water Resources, Hydrology Bureau, YRCC, pers. comm. October 2010; Xu et al. 2005).

The cumulative active storage capacity of the main Yellow River dams is approximately 31 × 109 m3 (Figure 31). The active storage is less than half that of the total storage capacity. The temporal pattern of increasing capacity to regulate the river suggested four suitable periods for examining the influence of regulation on the pattern of historical flows in the lower Yellow River: pre-Samenxia Dam; post-Sanmenxia Dam, which includes Liujiaxia Dam; post-Longyangxia Dam; and post-Xiaolongdi Dam. For the purpose of characterising the hydrological impact of these dams, ideally the post-Sanmenxia/Liujiaxia period would be split into two separate periods, but the disadvantage of this is that the shortness of the records would lead to the calculation of less reliable flow statistics. The Sanmenxia/Liujiaxia period is characterised by inconsistent regulation effects. The active storage capacity of Sanmenxia Dam was initially greater than that shown in Figure 31, and it had a large and direct influence on the hydrology of the lower Yellow River. As the influence of Sanmenxia Dam altered through loss of storage capacity and changed modes of operation, Liujiaxia Dam came into operation, but because it was located in the upper catchment its influence was less direct than that of Sanmenxia Dam. Of course, the post-Longyangxia and post-Xiaolongdi periods are also hydrologically complex, as the impacts of these dams were superimposed onto the impacts of the existing dams.

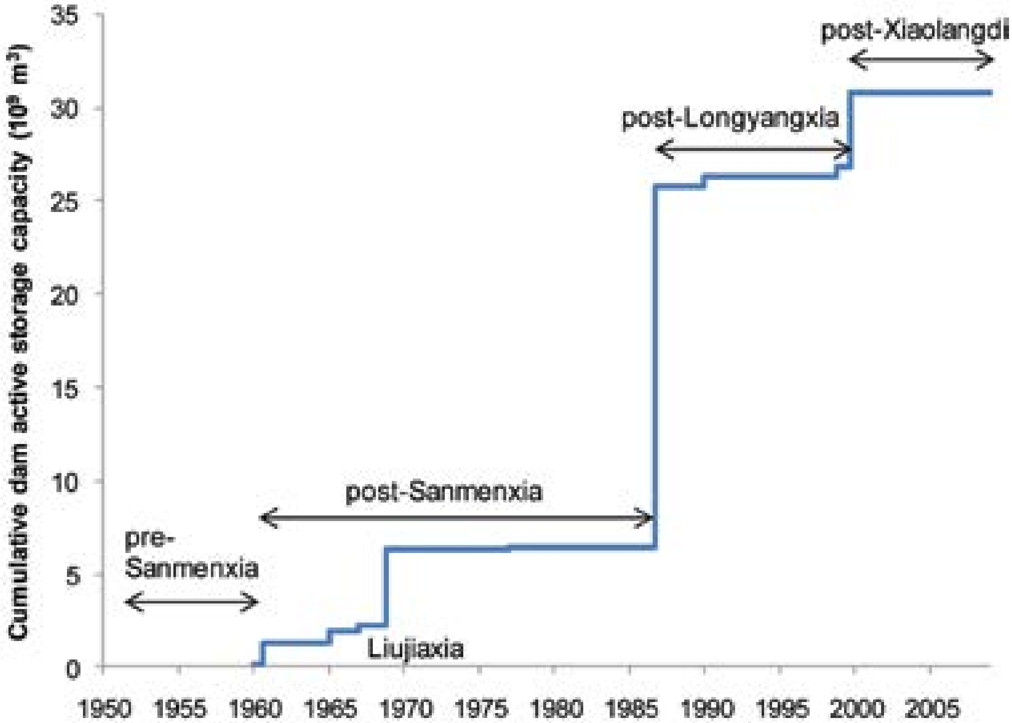
The period of main irrigation demand in the lower Yellow River begins in April and runs to June. WSDR releases for sediment flushing are made usually in the period late-June to July. July to October is the natural flood season. Until the end of August Xiaolangdi Dam level is kept below a certain threshold to retain sufficient capacity to absorb a major flood inflow. From September, most of the inflows are held in the dam for the needs of both winter ice-flood prevention and irrigation in the following season (Chen et al. 2009).

Diversion for irrigation involves the operation of off-takes that extract water, and return channels that deliver unused water back to the river. Bin et al. (2003) listed 26 irrigation districts along the lower Yellow River in the year 2000, all fed by various off-takes (see map in Kusuda, 2009, p. 49, depicting at least 36 off-take canals downstream of Huayuankou). Wang and Hu (2004) noted that there were 'hundreds' of water diversion facilities along the lower Yellow River, with a total capacity of about 1,500 m^3/s.

The lower Yellow River provides domestic water for large- and mid-sized cities along the river, including Zhengzhou, Kaifeng, Puyang, Jinan and Dongying. Through inter-basin water transfers, the Yellow River also provides water supply to Tianjin City and Cangzhou of Hebei Province, and to Qingdao of Shandong province. In addition, the Yellow River provides water for industrial uses, the central plain (Zhongyuan) oilfield (near Puyang, Henan, north of the Yellow River between Zhengzhou and Dongping) and Victory (Shengli) oilfield (near Dongying in the Yellow River Delta region).

Water has been occasionally transferred from the Yellow River to Tianjin and Cangzhou through the Weishan sluice (in Jinan, Shandong province) since 1972. As an example, the eighth diversion was made in 2003/2004, when over a 117-day period (from 12 September 2003 to 6 January 2004), 0.925 × 10^9 m^3 of water was diverted from the Yellow River at Weishan sluice (People's Daily Online, 8 January 2004). The purpose of water transfer from the Yellow River to Qingdao is to alleviate the water shortage of Qingdao City and water-deficient areas and areas with high-fluorine content along the transfer route. From 1989, after its completion, until May 2004, the volume of water abstracted from the Yellow River for transfer to Qingdao totalled 2.357 × 10^9 m^3 (unpublished data, YRCC).

Figure 31. Cumulative active storage capacity of major dams in the Yellow River basin from 1960 to 2008.



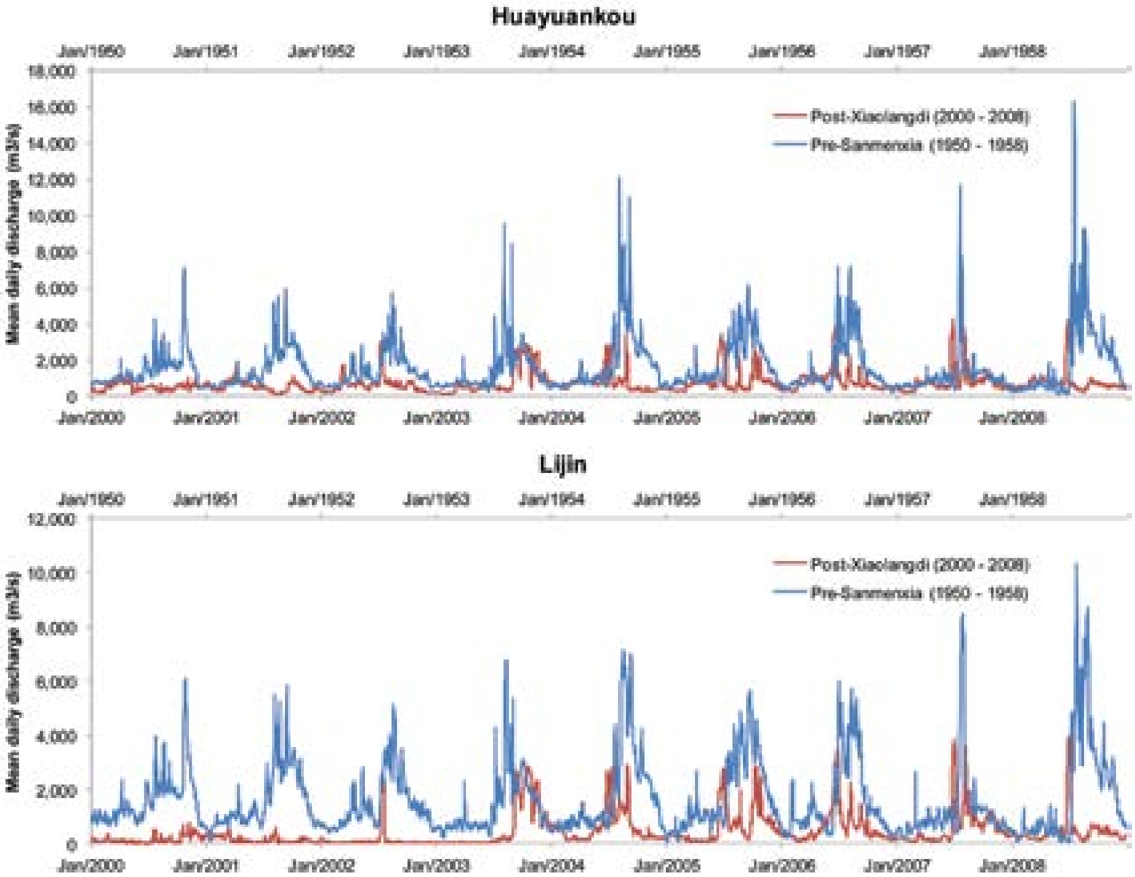
Note: Four main periods were identified for investigation of the hydrological impacts of regulation on the lower Yellow River.

The impact of diversions on the hydrology of the lower Yellow River is incremental down the river, and varies from year to year depending on demand. Evaluation of the impact of diversions was undertaken here through examination of the difference in the pattern of hydrology at four gauges between Xiaolangdi Dam and the Bohai (Huayuankou, Sunkou, Luokou and Lijin). A comparison of the most recent 9 years of flow data with 9 years from before operation of Sanmenxia Dam shows that at Huayuankou, from 2004 the spring snowmelt flow pulse was absent (March-April), the high flow event began earlier (by about one month), the high flow period had a much lower magnitude and duration of the flood peak, and the high flow period recession was much shorter (Figure 32). The impact of regulation was similar at Lijin, but with much lower baseflows during 2000 to 2003, and baseflows from 2004 onwards being higher, but still much lower than during the pre-Sanmenxia phase (Figure 32). While the majority of the differences in the pre-Sanmenxia and post-Xiaolangdi hydrographs can be attributed to flow regulation and water diversion, part of the difference may also be explained by climate change.

6.2 Trend in climate and runoff

In the process of environmental flow assessment, the natural flow components are characterised as a guide to the flow regime required to maintain river health (Gippel 2001). Natural flow components are best characterised from a naturalised *daily* flow series. The naturalised series represents the flows unimpaired by water resources development, but includes the effects of any land cover change. Naturalised *monthly* flow series have been modelled by The Yellow River Conservancy Commission as the sum of observed flows and water diverted to or from the system, and allowing for an estimate of water lost or gained through changed infiltration and evaporation from water bodies (Zhu and Zhang 1999; Li et al. 2001).

Figure 32. Comparison of 9-year long hydrographs for Pre-Sanmenxia phase and Post-Xiaolangdi phase at Huayuankou and Lijin gauges.



In cases where a naturalised *daily* flow series is not available (as is the case for the lower Yellow River), the magnitude, timing, frequency and duration of the natural flow components are typically characterised from a particular period of historical daily flow record, perhaps a period prior to regulation by dams when the river was known, or assumed, to be in good health. This characterisation is used to help define the flow components required to maintain river health, so it is important to know if this period was significantly wetter or drier than average, or later periods. As part of the environmental flow assessment process, the later post-dam period/s of record are also characterised to determine the relative impact of regulation on historical flows, so it is important to know if there is a natural change in the data that needs to be accounted for when interpreting the results. In a river with high consumptive demands, a significant natural declining trend in water volume has implications for current, and perhaps future, arrangements to share water between the environment and other users, so it is important to identify whether or not such a trend is present.

In hydrology, trend is a statistical term referring to the direction or rate of increase or decrease in the magnitude of observations of hydrological variables in a time series of data when random fluctuations of individual observations are disregarded. Generally two types of trend are considered, one being monotonic trend (steady change in one direction) and the other being a shift change (significant step change at a particular year, known as the change point).

Trend in observed river flow can be the result of:

- Non-random changes in climate, mainly in evaporation, rainfall amount, and rainfall intensity, which affect runoff volumes
- Changes in land cover, either natural or otherwise, that affect runoff volumes, particularly change from pasture/cropland to forest and vice-versa
- Changes in utilisation of water resources, such as those influenced by: construction of dams (large or small); altered rates of consumptive water use for social purposes such as agriculture, industry and drinking water; and, inter-basin transfer

Increased utilisation of water resources can result in a shift change (from dam construction, or rapid development of irrigation), or a monotonic declining trend due to gradual increase in water demand. The impact of these developments on river flow is best calculated directly – in trend analysis, water utilisation confounds any signal from natural climate and land cover changes. From the perspective of environmental flow assessment, the main question is whether the natural flow has changed. For example, if the natural flow has declined since the pre-regulation period, then the pre-regulation discharge time series may not be an exemplar for defining the characteristics of the flow components required for river health under current hydrological conditions. Thus trend analysis is ideally undertaken on a naturalised discharge time series.

6.2.1 Basin climate trend

There is a large body of literature concerning trend in the hydrology of the Yellow River. Convincing evidence has been presented that, although spatial variability is evident, overall basin rainfall has declined since the 1950s and 1960s, with a major decline occurring from the 1990s. Also, climate warming, increased evaporation, and declining rainfall erosivity trends have been identified (Liu and Zhang 2002; Yang et al. 2004; Xia et al. 2004; Liu and Zhang 2004; Liu and Xia 2004; Fu et al. 2004; Zhang et al. 2004; Xu 2005; Wang et al. 2006; Chang et al. 2007; Yang et al. 2007; Zhang et al. 2008; Zhao et al. 2008; Liu and Cui 2010; Ma et al. 2010; Lan et al. 2010, Xin et al. 2010). A dry spell comparable to that experienced in the 1990s also occurred between 1922 and 1932, when the average runoff was 30 per cent below the river's long-term average (Liu and Zhang 2002; Xu et al. 2005). Analysing precipitation data from the period 1960–2006 from across the basin, Liu et al. (2008) found the change point, when rainfall declined abruptly, ranged from 1963 to 1998, with the abrupt changes in the lower reaches appearing earlier than those in the middle and upper reaches. Analysing trend in air temperature, precipitation, sunshine duration and pan evaporation at 23 meteorological stations in the headwater catchment of the Yellow River basin from 1960 to 2001, Zhao et al. (2008) found that using the moving t-test and Yamamoto method, abrupt changes happened in the 1980s. Using the Mann-Kendall method, abrupt changes of temperature and precipitation took place in the early 1990s, and that of pan evaporation occurred in the 1960s.

While it is generally believed that the climate trends observed in The Yellow River basin since the 1950s are consistent with the pattern of global climate change, such as that reported by the Intergovernmental Panel on Climate Change (IPCC), (e.g. Fu et al. 2004; Xia et al. 2004; Wang et al. 2006; Zhang et al. 2008; Lan et al. 2010), there is also evidence that the recent drying phase could be part of a longer cycle. Zheng et al. (2005) reconstructed an annual time series of precipitation in the middle and lower Yellow River basin over the period 1736–1910 using the rainfall and snowfall archives of the Qing Dynasty and combined this with observed data up to the year 2000. They found that an abrupt change in precipitation from high to low occurred around 1915 over the middle and lower reaches of the Yellow River. The periods of 1791–1805, 1816–1830 and 1886–1895 were markedly wet and the periods 1916–1945 and 1981–2000 were markedly dry. Three periodicities of 22–25 years, 3.9 years and 2.7 years were evident in the precipitation fluctuation. The periodical signal of 22–25 years became weaker since the abrupt change of 1915 and disappeared in the late 1940s, to be replaced by a periodical signal of 35-40 years. Using the same 1736-2000 time series, Hao et al. (2008) found evidence of inter-annual and inter-decadal oscillations of 2–4 years, quasi-22 years and 70–80 years. The 70–80 year cycle coincided for the entire series with the Pacific decadal oscillation (PDO), a pattern of Pacific climate variability that is the sum of several processes with different dynamical origins. Using a range of data sources, Qian W et al. (2007) found that climatic time series from northern China showed temporal and regional patterns in the last two to three centuries, including two multi-decadal oscillations at quasi-20 year and quasi-70 year timescales. For the precipitation series, the dry anomalous event was found in the late 1920s, while the wet anomalous event occurred in the 1950s. A severe drought in 1927–1929 in northern China coincided with the anomalous warm and dry decade (Qian W et al. 2007).

6.2.2 Basin land cover changes

Soil and water conservation measures (tree planting and terracing activities) began in some areas of the Yellow River catchment in the 1950s, but prior to 1980 deforestation was a serious problem (Fu et al. 2004). The deforested areas have been partially recovered since establishment of the Three North (Northeast-North-Northwest) Forest Zone Project (established in 1978) and the Natural Forest Protection Plan (NFP) (established in 1998) (Fu et al. 2004; Cheng, 2009). As part of the NFP, the nationwide crop set-aside Grain for Green policy (also known as the Sloping Land Conversion Program), which began in 1999, aims to convert around 14.7 × 10^6 ha of cropland to forest (Xu et al. 2004; McVicar et al. 2007; Zhou et al. 2012). In the Yellow River basin, reafforestation measures are mainly intended to reduce sediment yield from the Loess Plateau (Chen and Cai, 2006), but this practice can also lead to reductions in water yield.

6.2.3 Basin historical runoff trend

Based on a time series of streamflow data from Sanmenxia over the period 1470-2007, Miao and Ni (2009) identified that the most persistent droughts occurred in the period 1868-1990. Sustained low flows also typified the periods 1470s–1490s, 1920s–1930s and 1990s–2000. Miao and Ni (2009) also identified oscillation *circa* 11-year, 26-year, 67-year and 120-year, with the periodicity of the 120-year being the strongest. Strong relationships between patterns of runoff and ENSO (El Nino Southern Oscillation) have been identified in records from both the upper basin (Lan et al. 2003) and lower basin (Wang et al. 2006).

A number of studies have demonstrated a decreasing trend in observed runoff in northern China since the 1950s, with the strength of the trend increasing in the downstream direction (Ren et al. 2002). For the 12 km^2 Luergou upper Yellow River sub-catchment near Tianshui City, Gansu Province, Wang et al. (2008) found no statistically significant trend in runoff over the period 1982–2003. Using the Mann-Kendall test, Fu et al. (2004) found no significant trend in annual runoff at Lanzhou (1952–1997), but runoff increased significantly during winter and spring, and decreased during the summer and autumn. The observed annual runoff at Huayuankou and Lijin stations showed significant decreasing trends. A total of six months showed a decreasing trend at the Huayuankou station and all of them fell within the rainy season, so an annual decreasing trend resulted. There were eleven months with a significant decreasing trend at Lijin station. In the upper Yellow River basin, Zheng et al. (2007) found that, using the Mann-Kendall test, runoff records from Huangheyan, Jimai, Maqu and Tangnag gauges showed no significant trend for the period 1956 to 2000. However, change-point analysis showed that a significant reduction in annual stream flow occurred around 1990. Splitting the series into the two periods 1956–1990 and 1991–2000 revealed a reduction in mean annual streamflow in the 1990s of up to 51 per cent. Feng et al. (2006) also noticed a reduction in the annual flows for two of these upper basin gauges during the 1990s compared to the period 1970–1980. Wet-season rainfall appeared to be the main factor responsible for the decreasing trend in annual streamflow. In terms of relative reduction, low flows were more impacted than high flows (Zheng et al. 2007). Miao et al. (2010) used the Mann-Kendall test to analyse trend in historical data from 15 Yellow River basin gauging stations (10 of which were on the mainstem of the river) over the period 1956–2007. All but the most upstream station showed a significant declining trend. The trends also showed step change. For the lower river stations, the years of the change points were Huayuankou (1990); Gaocun (1988); Aishan (1985); and Lijin (1985). Of all stations examined, the greatest difference in runoff before and after the abrupt change occurred at the Lijin station, where the average annual discharge reduced by 63 per cent. Yang et al. (2009) applied Mann-Kendall trend analysis to low flow statistics calculated from seven hydrological stations in the Yellow River basin for the period 1955–2005. The major hydrological conditions for low-flow were identified to have no trend in the upper Yellow River, and downward trends in the middle reach and at Lijin. Huayuankou was an exception, showing no trend in low flow statistics. Zhang et al. (2009) analysed for trend in low flow (10^{th} percentile) and high flow (90th percentile) statistics calculated for historical data from the period 1950s-2005 for six Yellow River basin gauging stations. In general, there was a declining trend for high flows an increasing trend for low flows. The timing of step changes of high flows ranged between 1985 and 1995, and that of low flows ranged between 1975 and 2000.

6.2.4 Basin naturalised runoff trend

As well as the historical flow series, Fu et al. (2004) also analysed the naturalised flow series over the period 1952–1997 for Lanzhou, Huayuankou and Lijin. The results of the Mann-Kendall trend test for natural monthly runoff showed some differences compared with that of historical monthly runoff. The increasing trend for winter and spring at Lanzhou disappeared, suggesting that the increasing trend resulted from regulated stream flow due to dam control. At Huayuankou only January, August, November and December (plus the annual series) showed a significant decreasing trend. The result was similar at Lijin, but with January also showing a decreasing trend and March an increasing trend. Liu and Zheng (2004) also analysed the 1952–1997 naturalised annual flow series using the Mann-Kendall trend test. They found that there was no trend in the data from Lanzhou, but there was a significant declining trend for data from Huayuankou. Wang et al. (2006) estimated that the average annual natural discharge at Lijin over the 1990s (41.9 × 10^9 m^3) was 30.5 per cent less than the average in the 1950s (60.3 × 10^9 m^3). Li and Yang (2004) split the natural runoff time series from 10 gauges in the Yellow River basin into the two periods 1956–1979 and 1980–1998, presumably on the basis that a step change occurred in 1980. At Lijin, the data suggested a reduction of 74.7 × 10^8 m^3 (equivalent to about 13%) over these two periods.

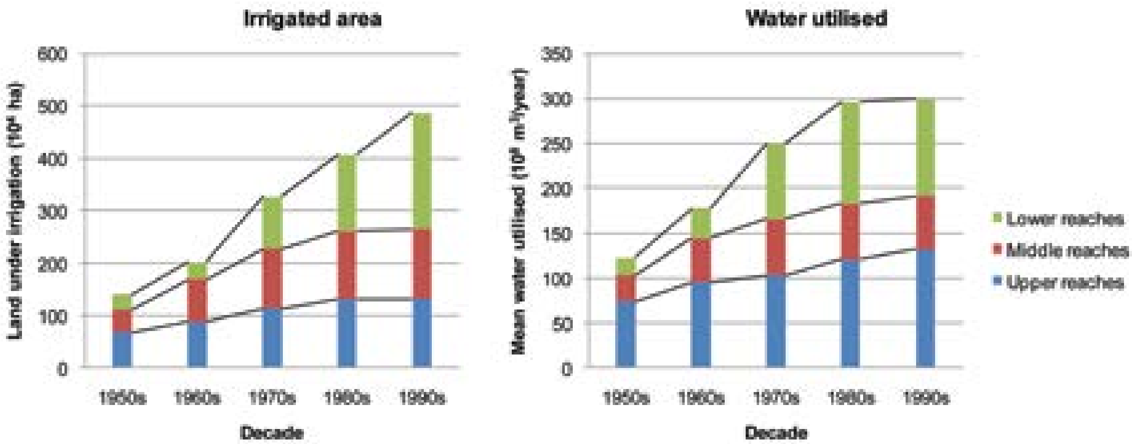
Using data sourced from YRCC, Giordano et al. (2004, p. 18) reported that the annual runoff ratio (ratio of naturalised runoff to rainfall) fell in the 1990s compared to the previous three decades. Whether this was statistically significant was not reported. Liu and Zheng (2004) also noted a decline in the runoff ratio over the period 1952-1997, with a change point at 1968. The decrease in annual discharge associated with the reduced runoff ratio was about 5.6 × 10^9 m^3, or about 9 per cent of the average annual discharge. Giordano et al. (2004) suggested that the reduction in the runoff ratio may partly reflect failure of the natural flow modelling procedure to account for all of the water resource development. For example, it would be difficult to account for the hydrological effect of the many small storages built for water and soil conservation. Nonetheless, at least part of the decline in the runoff ratio could be associated with revegetation efforts.

6.2.5 Attribution of trend in basin runoff

Fu et al (2004) attributed the changes in historical runoff to: increased demand for water due to increased population, increased area of land under irrigation, increased dam storage volume and evaporative surface area, groundwater exploitation increasing infiltration, inter-basin water transfer to Talimu River for ecological use and Tianjin and Qingdao for domestic use, and increased agricultural, industrial, and domestic consumption. Temperature and runoff trends were thought to be consistent with predicted climate change impacts. Coal mining is the largest industry in the Yellow River Basin and the associated storage areas could impact runoff patterns. Fu et al. (2004) noted that although the impact of the coal industry on hydrology in the Yellow River has not been reported, it can be assumed that development of coal mining, along with development in the oil, steel, iron and metal mining industries, has increased water demand.

The area of land under irrigation in the Yellow River basin increased markedly from the 1950s to the 1990s (Figure 33). Agricultural irrigation accounts for about 91 per cent of the total water consumption in the basin (Liu and Xia, 2004), so the pattern of basin water utilisation also increased from the 1950s (Figure 33). The volume of water utilised levelled off in the 1980s and 1990s, despite an increase in the area under irrigation in the lower basin (**Figure33**), and this is likely due to efficiency gains.

Figure 33. Decadal average area of land under irrigation and volume of water used in the Yellow River basin.



Data sourced from Liu and Zhang (2002).

There is evidence from some Yellow River sub-catchments that extensive soil and water conservation measures have been associated with a significant reduction in annual flows, baseflows and peak flows (Bardsley and Liu, 2003; Huang and Zhang, 2004; Sun et al 2006; McVicar et al 2007). At the sub-catchment scale, Sun et al. (2006) suggested that the Loess Plateau region, with its deep loess soils (i.e. 10–100 m), would likely have a large reduction of water yield from reafforestation (i.e. up to 50 per cent reduction for full conversion of cropland to forest). Sun et al. (2006) also expected that soil and water conservation practices such as bioengineering techniques that are commonly used on eroded hillslopes to help seedling establishment would also increase surface roughness, reduce overland flow, and increase soil water storage. These conditions would increase evapotranspiration and reduce annual total water yield. However, Sun et al. (2006) agreed with Tang (2004 cited by Wang et al. (2006)), that because large areas of croplands are needed to meet food demands, at the basin scale the increase in percentage forest cover would be relatively small. Tang (2004) estimated that in the upper and middle Yellow River basin, the decrease in surface runoff from soil conservation measures over the period 1980–1997 represented only 1.2 per cent of the natural runoff from that period. Liu and Zheng (2002) quoted an estimate of 1 × 10^9 m^3 reduction in water yield in the middle reaches of the Yellow River due to soil conservation works undertaken in the period 1970-1984.

For the source region of the Yellow River, Chang et al. (2007) hypothesised that 70 per cent of the observed discharge reduction from 1955 to 2005 resulted from climate change, and the remaining 30 per cent may have been caused by intensified human activities such as population growth and over-grazing. Using data from the period 1956–2000, Liu and Zhang (2004) found that reduced precipitation was responsible for 75 per cent of the observed reduction in river discharge in the upper basin and 43 per cent of the reduction in the middle basin. With respect to water discharge to the sea, Wang et al. (2006) attributed 51 per cent of the decrease in the 1990s, compared to the 1950s, to the natural impacts including decreasing regional precipitation, and the remaining 49 per cent to anthropogenic impacts in the river drainage basin. Xu (2005) estimated that:

- the contribution of water diversion and consumption to the reduction in annual discharge at Lijin over the period 1970–1997 was 41.3 per cent
- the contribution of precipitation was 40.8 per cent
- the contribution of temperature was 11.4 per cent
- the contribution of erosion and sediment control measures was 6.5 per cent.

Liu and Zheng (2002) were of the opinion that increased water utilisation was responsible for 80 per cent of the observed reduction in runoff in the 1990s.

6.2.6 Lower Yellow River naturalised monthly flow series trend (1952–2008)

Trend analysis was repeated for the two lower Yellow River stations Huayuankou and Lijin, using updated naturalised monthly runoff series from the period 1952-2008, as supplied by YRCC. The trend analysis was undertaken using TREND trend/change detection software (Chiew and Siriwardena 2005). TREND has 12 statistical tests, based on the WMO/UNESCO Expert Workshop on Trend/Change Detection and on the Cooperative Research Centre for Catchment Hydrology publication *Hydrological Recipes* (Grayson et al. 1996). Here, the non-parametric Mann-Kendall test for trend and CUSUM test for step change were preferred to the parametric tests in order to avoid the requirement of normality in the distribution of the data. Statistical significance was tested using a two-sided tail test at $\alpha \leq 0.05$.

A significant declining trend was evident in monthly discharge in most months, and also in annual discharge, at both Huayuankou and Lijin (Table 14). March and June had no trend for both stations and April had significant trend only at Huayuankou. August to December had a significant step change evident at both stations (Table 14). Most of the change points fell within the range 1984 to 1990, but December had an abrupt change in 1968 at both stations, and earlier step changes were also evident in January and August at Huayuankou (**Figure 34**). These results essentially confirm the earlier studies of Fu et al. (2004) and Liu and Zheng (2004) that analysed the same data but over a shorter time series. The main difference is that the longer series examined here showed a significant declining trend for all of the summer-autumn high flow months and the high flow recession into winter. The years of step change revealed here correspond roughly with those reported by other authors who analysed historical time series from these stations.

The change point for the step change in the annual series at Lijin occurred in 1990 (Figure 34). If the natural series is split at the change point, the mean annual natural discharge prior to the step change was 61.7 × 10^9 m^3 and after the step change it was 43.9 × 10^9 m^3 (Figure 35). The latter value is a more realistic estimate of the current water resources availability at Lijin than the value of 58 × 10^9 m^3 that is commonly cited in the literature (e.g. Ongley 2000; Bin et al. 2003; Xia et al. 2002; Liu and Zheng 2002; Li et al. 2003; Chen et al. 2003; Xia et al. 2004; Xu et al. 2005; Ma et al. 2010). [16]

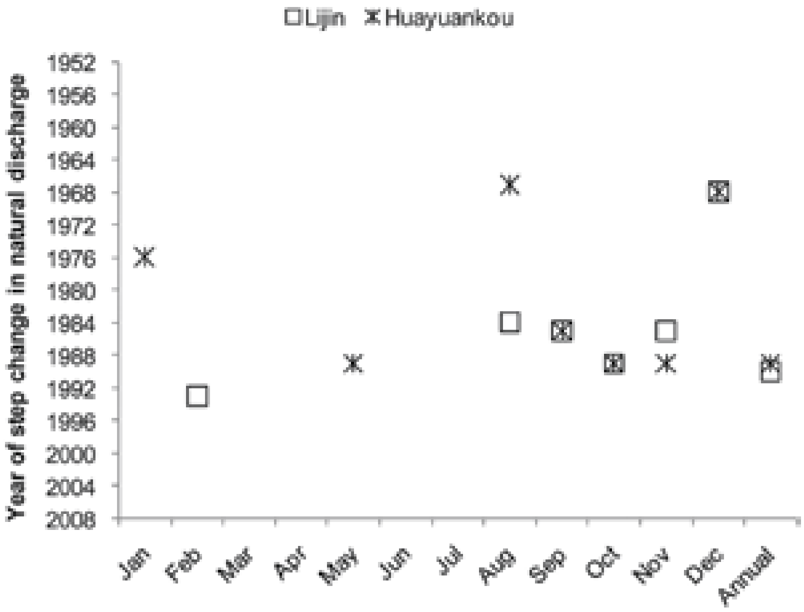
16 The origin of the value of 58 × 10^9 m^3 for mean annual basin runoff appears to be an estimation made some time ago by YRCC of the naturalised streamflow at Huayuankou for the period 1919 - 1975 (55.9 × 10^9 m^3) and then adding an estimate of the natural contribution from tributaries between Huayuankou and Lijin (Chen et al. 2003; Xu et al. 2005). Others have quoted different values of mean annual naturalised basin runoff, e.g. Zhu et al. (2003) and Zhu et al. (2004) gave a value of 57 × 10^9 m^3 for 1956–2000 and 43 × 10^9 m^3 for the 1990s, Ren et al. (2002) gave a value of 59.2 × 10^9 m^3, and Wang et al (2008) gave a value of 68.8 × 10^9 m^3. Quoting Institute of Water Resources and Hydropower Research (1998) Fuggle et al. (2000, p. 18) gave a value of 74 × 10^9 m^3, but this figure would also include groundwater resources.

Table 14. Significance of trend and step-change tests for Huayuankou and Lijin naturalised monthly runoff data, 1952–2008.

Period	Monotonic trend (Mann-Kendall)		Step change (CUSUM)	
	Huayuankou	Lijin	Huayuankou	Lijin
Jan	S (0.01)	S (0.01)	S (0.01)	NS
Feb	S (0.01)	S (0.05)	NS	S (0.05)
Mar	NS	NS	NS	NS
Apr	S (0.05)	NS	NS	NS
May	S (0.01)	S (0.01)	S (0.05)	NS
Jun	NS	NS	NS	NS
Jul	S (0.05)	S (0.05)	NS	NS
Aug	S (0.01)	S (0.01)	S (0.05)	S (0.01)
Sep	S (0.01)	S (0.01)	S (0.05)	S (0.05)
Oct	S (0.05)	S (0.05)	S (0.05)	S (0.05)
Nov	S (0.01)	S (0.01)	S (0.05)	S (0.01)
Dec	S (0.01)	S (0.01)	S (0.05)	S (0.01)
Annual	S (0.01)	S (0.01)	S (0.01)	S (0.01)

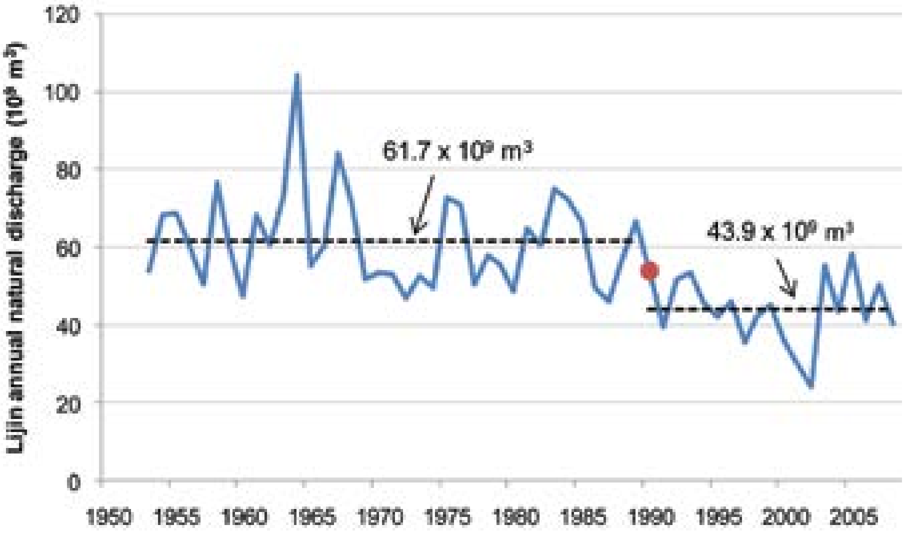
Note: All trends are declining through time.

Figure 34. Years of significant step change using the CUSUM test for Huayuankou and Lijin naturalised monthly runoff data, 1952–2008.



Note: All step changes are declining with time.

Figure 35. Naturalised annual runoff series at Lijin, showing mean annual discharge for periods before and after the change point in 1990.



Note: Data are from 1953 to 2008, with annual flow calculated over the water year beginning in December of the previous year.

The non-parametric Wilcoxon Rank Sum test was applied to the naturalised discharge series to investigate whether there were significant natural differences in median discharge of the periods of record selected for characterisation of historical (regulated) hydrology. A significant difference would mean that differences identified in the hydrological characteristics through the historical record might be partly associated with natural change, as well as with flow regulation. The reference period was 1952–1959 (pre-Sanmenxia Dam), and this was compared with the subsequent regulated test periods 1961–1985 (post-Sanmenxia Dam); 1987–1998 (post-Longyangxia Dam) and 2000–2008 (post-Xiaolangdi Dam). Note that the years when the dams commenced operation were excluded from the periods of record as these years were partly pre-dam and partly post-dam. The Rank Sum test indicated that in most cases there was no difference in the median flows between these selected periods (Table 15). Where statistical differences were evident, in some cases the median monthly flows in the later flow periods were lower than those of the test period and in other cases higher (Table 15). Thus, there was no consistent pattern of flow change in the natural series that corresponded with the periods of record selected for analysis of the impacts of flow regulation on historical flows. This result was not unexpected, because the trend analysis indicated that although the flows were characterised by a declining trend, the major decline began around 1984-1990. The median monthly flows over the period 2000-2008 were lower than those of the period 1952-1959 for every month, but the differences were not significant because of the short periods of record and high variability of the data.

The literature suggests that although there are longer-term cycles evident in the climate records, a drying period began in the 1980s to 1990s, and this was reflected in generally declining natural runoff, especially in the wet season, and more evident in the lower basin. In some records a step change in runoff was apparent beginning somewhere in the period 1985 to 2000, depending on location and the hydrological statistic being examined. These results were confirmed here in a re-analysis using longer time series. While Qian W et al. (2007) suggested that a wet anomalous period occurred in the north of China in the 1950s this was not apparent in the naturalised flow data from the lower Yellow River. It was established here that there was no consistent pattern of natural hydrological change that corresponded with the main periods of river regulation by dams. Thus, it is concluded that the pre-Sanmenxia reference period is suitable as an exemplar for characterisation of natural flow components, although it must be remembered that the lower Yellow River was already affected by regulation in the 1950s. The later regulation, beginning with Sanmenxia Dam in 1960, was superimposed on a natural trend of declining runoff due to falling rainfall and increased temperatures. The period corresponding to post-Sanmenxia Dam and pre-Longyangxia Dam (1961–1985) was not noticeably drier or wetter than the pre-Sanmenxia period. However, over the period 1984–1990 the natural runoff transitioned through a step change to lower natural runoff. Thus, the period corresponding to post-Xiaolangdi Dam (1999–2008) was noticeably drier than the periods before. This means that interpretation of the severity of any hydrological changes apparent in the historical flow records after the commencement of Xiaolangdi Dam needs to take this into account.

Table 15. Results of Wilcoxon Rank Sum test for difference in medians of selected periods of record for Huayuankou and Lijin naturalised monthly runoff data, 1952–2008.

Period	1952–1959 (pre-SM) v 1961–1985 (post-SM)		1952–1959 (pre-SM) v 1987–1998 (post-LY)		1952–1959 (pre-SM) v 2000–2008 (post-XL)	
	Huayuankou	Lijin	Huayuankou	Lijin	Huayuankou	Lijin
Jan	NS	NS	S < (0.05)	NS	S < (0.05)	NS
Feb	NS	NS	NS	NS	NS	NS
Mar	S > (0.05)	S > (0.05)	NS	NS	NS	NS
Apr	NS	NS	NS	NS	NS	NS
May	S > (0.05)	S > (0.01)	NS	NS	NS	NS
Jun	NS	NS	NS	NS	NS	NS
Jul	NS	NS	NS	S < (0.05)	NS	NS
Aug	NS	NS	S < (0.01)	S < (0.01)	S < (0.05)	S < (0.05)
Sep	NS	NS	S > (0.05)	S > (0.05)	NS	NS
Oct	NS	NS	S > (0.05)	NS	NS	NS
Nov	NS	NS	S > (0.01)	S > (0.01)	NS	NS
Dec	NS	NS	NS	NS	NS	NS
Annual	NS	NS	NS	NS	NS	NS

SM = Sanmenxia Dam operating, LY =Longyangxia Dam operating and XL = Xiaolangdi Dam operating. The symbol < or > with S indicates whether the median of the test period was significantly less than or greater than that of the reference period. NS means not significant at $\alpha \leq 0.05$.

6.3 Consumptive water utilisation (1952–2008)

Flow in the lower Yellow River is now largely controlled by managed releases from Xiaolangdi Dam, and then further downstream through numerous sluices and other diversions and outfalls associated with irrigation, industrial and domestic supply. Three major tributaries enter the river downstream of Xiaolangdi Dam. In downstream order they are Yiluohe (Yihe and Louhe system), Qinhe and Xiaoqinghe (Dawen-Daqinghe system), with Yiluohe and Qinhe joining the Yellow River upstream of Huayuankou gauging station.

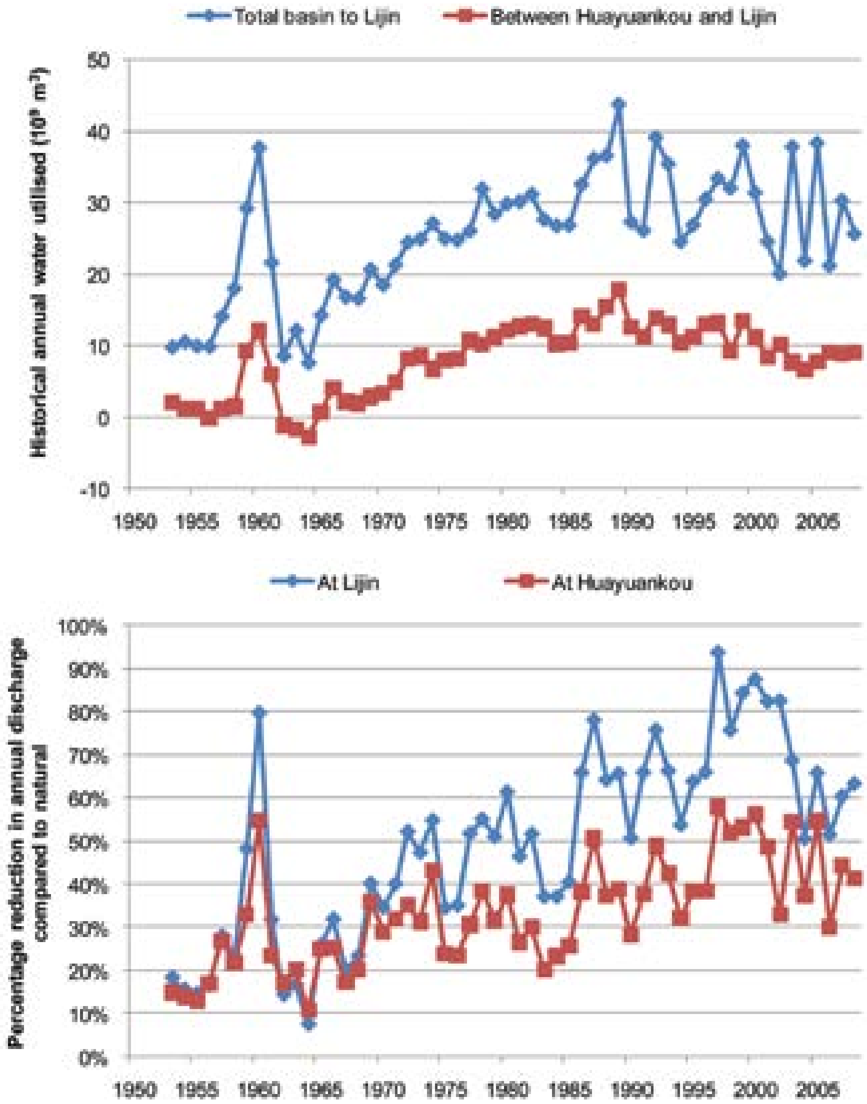
It is of interest to know the temporal pattern of water utilisation in the lower Yellow River, as this is one of the major determinants of how much water remains in the river. Water utilisation for the basin measured at Lijin was calculated by subtracting the historical flow from the naturalised flow (Figure 36). The volume of water utilised in the river between Huayuankou and Lijin was estimated as the difference between the volume utilised as measured at Lijin, and the volume utilised as measured at Huayuankou (Figure 36).

The completion of the People's Victory Canal (PVC) in 1952 marked the beginning of the diversion of water from the Yellow River to surrounding irrigation districts (Bin et al 2003). Very little water was taken from the Yellow River downstream of Huayuankou prior to 1959, although in the wider basin, an average of about 10×10^9 m^3 was used each year from 1953 to 1956 (Figure 36). Under the period of the Great Leap Forward (1958 to 1961) the irrigated area in the Yellow River basin increased 58 times from 37,500 ha in 1957 to 2,170,000 ha at the end of 1959 (Bin et al 2003). In 1959, 1960 and 1961 the volume of water diverted rose dramatically (Figure 36). Also, Sanmenxia Dam was constructed during this period, with work beginning in April 1957 and the project completed and operational in October 1960 (Chen and Liu 1988). The regulation of flow by the dam helped facilitate the rapid expansion in water utilisation.

The remarkable expansion of water utilisation in the three-year period 1959–1961 produced a dramatic rise in the water table, with waterlogging and salinity rendering large areas unproductive (Bin et al. 2003). In 1962 the Henan Provincial Government ordered the closure of most of the water diversion systems along the Yellow River, and the irrigation districts were instructed to undertake salinity control measures (Bin et al. 2003). After 1965 the irrigation districts resumed operation and the agricultural production grew steadily (Bin et al. 2003) (Figure 36). In the 1970s conjunctive use of surface and groundwater was adopted (Luo et al. 2006). Under the economic reforms initiated in 1978 (Webber et al. 2008), the area under irrigation and total water use continued to increase (Fu et al. 2004). In the Yellow River basin, industrial production is most intense in Shandong province (Webber et al. 2008). Industrial uses of water in the basin increased by 74% between 1980 and 1993 (Heilig 1999). In the same period, urban uses of water increased by 245% (Heilig 1999).

After increasing steadily since 1965, water utilisation in the reach between Huayuankou and Lijin began to decline after 1989 (Figure 36). Water utilisation for the whole basin also generally declined after 1989, but it was more variable (Figure 36). The turning point in water utilisation coincided with the step change decline in naturalised runoff (Figure 34 and Figure 35). While the absolute volume of water utilised began a declining trend in 1989, the percentage of the flow taken from the river continued to increase, reaching a peak in 1997, when, at Lijin, 94% of the natural flow was utilised, and at Huayuankou it was 58% (Figure 36). Since 1997, the relative volume of water utilised has varied, but it has generally followed a declining trend (Figure 36).

Figure 36. The historical annual volume of water used for the basin measured at Lijin, the volume used between Huayuankou and Lijin, and the percentage reduction in annual natural discharge at Lijin and Huayuankou.



Note: Data are from 1953 to 2008, with annual flow calculated over the water year beginning in December of the previous year.

6.4 Navigational use of the river

By end of Qing Dynasty and early in the Republic of China, with the construction of highway and railway networks, navigation on the Yellow River became less important than in previous periods. Currently, only short distance and seasonal transportation by shipping for passengers and goods takes place on some sections of the main channel. In the lower Yellow River there was very little navigational use in the 1990s due to low river levels (YRCC, no date).

6.5 Ice flood control

The lower Yellow River commonly freezes over in winter with the downstream, higher latitude, sections most prone to ice (Ye et al. 1999; Qian D et al. 2007). From Huayuankou to Gaocun flowing ice dominates, and the probability of freezing is less than 20 per cent (Ye et al. 1999). Downstream of Sunkou the air temperature is lower, the channel narrow and meandering, and ice dams can readily form. The downstream reaches are the first to freeze, which tends to obstruct flow originating from upstream, warmer reaches, creating a flood risk. Similarly, downstream reaches stay frozen longer into the spring than upstream reaches, again blocking the flow and causing flooding (Qian D et al. 2007; Giordano et al. 2004).

The ability to control the river's flow by dams has changed the ice regime of the Yellow River (Ye et al. 1999; Qian D et al. 2007). Formerly, the river froze over at a relatively small flow rate, so the frozen layer was low in the channel and the discharge capacity under the ice was small. When discharge increased rapidly, the ice could break up suddenly. When ice began to break up and float downstream, if the ice in the downstream reaches was still frozen, an ice dam was likely to form, followed by flooding (Ye et al.1999). Sanmenxia and Xiaolangdi Dams are managed in harmony to increase the flow during the freeze up period, which delays the onset of freezing and creates a greater capacity under the ice when it does freeze. During the thaw, the flow is controlled so as to delay the ice melt period. During the 1950s and 1960s freeze-up started on average on 28 December and the ice was completely melted by 12 February (Ye et al. 1999). After the full operation of Sanmenxia the freeze-up date was postponed until 6 January and the melting date was delayed until 28 February. This eliminated the problem of sudden ice break up. Qian D et al. (2007) claimed that operation of Xiaolangdi Reservoir from 2001 onwards has essentially solved the ice-flood issue of the Yellow River in the Shandong section. However, reports of ice-flood risk in Shandong persist in the media (e.g. People's Daily Online, 27 December 2002; China Daily 28 February 2005).

Empirical models have been developed to relate ice regime based on air temperature and ice density. Other models are based on thermodynamics, river hydraulics and practical experience (Ye et al. 1999). Thus the YRCC has available good predictive power with respect to ice flood control.

Results reported by Qian D et al. (2007) indicated that when water emerging from the reservoir is 4°C, if the flow during the freeze-up is controlled at around 500 m^3/s, the river channel will remain unfrozen upstream of Gaocun even in a very cold year. After the operation of Xiaolangdi Reservoir, the temperature of released water has been about 8–9 °C, which has effectively reduced the risk of ice jams. The average length of frozen river over the period 2001–2007 was 129 km, which is half of the average length observed over the period 1950–2000 (Qian D et al 2007).

6.6 Characterisation of environmental flow components

6.6.1 Rationale of flow components

Although the flow in a river varies continuously from nothing or low flow up to major floods, most conceptual models exploring the influences of flow variation on river ecosystems identify key flow components (parts of the flow regime) that serve important physical and biological functions (e.g. maintaining the channel morphology, sufficient minimum habitat during periods of low flow, or flow to stimulate fish spawning). Flow components fall into three main categories (Table 16). Flow components are the building blocks of environmental flow recommendations. When fully specified, a suite of flow components forms a flow regime that can be implemented by river operators to maintain river health at a certain level. The flow components have hydrological characteristics that require specification so that they can be implemented into a practical flow regime (Table 16). The specifications are made with an (explicit or implicit) understanding that they would have a high probability (i.e. low risk) of achieving their intended ecological objectives. Thus, certainty of achieving a high level of river health would likely require a suite of flow components with a high water demand, while the suite of components required to achieve a modest level of river health would likely require less water. Thus, flow components can be specified in different ways to create environmental flow options with different expected river health outcomes and different implications for sharing available water resources among the various users. The specifications for flow components listed in Table 16 are the minimum requirements that would enable a flow regime to be implemented. Depending on the circumstances, many other details may be required in order to specify a set of practical operating rules that would allow implementation of the environmental flow regime as intended.

Table 16. Flow components that comprise the flow regime.

Flow component categories	Sub-components	Characteristics of flow components
Baseflows	High and low flow seasons, or monthly baseflows	Season/ or month of year Magnitude a minimum threshold, below which diversion should cease
Cease to flow events Perennial rivers: no cease to flow events Intermittent and ephemeral rivers: cease to flow events should occur		Annual frequency Inter-annual frequency Timing Duration
Flow events	Flow pulses High-flow season Low-flow season Bankfull flow Overbank flow	Magnitude Annual frequency Inter-annual frequency Timing Duration Maximum rate of rise Maximum rate of fall

There are three basic types of knowledge that are typically used to specify the flow components that will achieve a given level of river health at low risk:

- characterisation of the river's hydrology (in particular the natural or unimpaired hydrology when river health was assumed or known to be at a high level, and if the river is regulated, the historical hydrology)
- relationships between flow magnitude and availability of hydraulic habitat (expressed in terms of water depth, velocity and bed shear stress)
- ecological and geomorphological knowledge of the hydraulic and hydrological regime requirements to achieve objectives that will maintain key ecological assets at a given level of health.

This section of the report is concerned with compiling the information base for the first knowledge-type above.

6.6.2 Data availability

Characterisation of flow components is best done using daily flow data. Monthly flow data are not suitable, because the high frequency peaks and troughs of flow, some of which may be critical to the biota, are not apparent in monthly data. An argument could be made that peak daily flow data are required, because some flow events, such as those that briefly inundate a bench to flush carbon to the river, or momentarily mobilising bed sediments, may not require flow to be at that level for an entire day, or more than one day. In China, peak daily flow data are not normally available, but mean daily flow should be available wherever there are streamflow gauges.

Characterisation of natural flow components is best done using data from a period of time when the flow was unregulated. It may be acceptable to characterise the flow components from a period of time when the flow was regulated to some degree, but the ecology was known to still be in a healthy state. Ideally, a naturalised flow record would be used (a modelled flow series, with the effect of water resources development removed). The advantage of a naturalised flow series over a pre-regulation historical series is that the modelled data are generated for a long time period (thereby allowing for more reliable statistics to be calculated), and the modelled natural series can be compared directly with the historical regulated series over the same time period (thereby eliminating any confounding influence of climate change or land-use change). While naturalised flows have been modelled at a monthly time-step in some places in China, including the lower Yellow River, such data are not available at a daily time-step. So, for this report, historical gauged mean daily flow data were used. The data were supplied by YRCC.

The lower Yellow River was divided into four reaches for the purpose of the environmental flow assessment (Table 12). The hydrology of each reach was characterised on the basis of data from a gauge located within the reach (Table 17). The gauges had data available for different length periods, and the early parts of the records had data gaps, so only the continuous time series were used (Table 17).

The Lijin station, with a catchment of 751,869 km^2 (99.9 per cent of basin total) is the last hydrological station before the river reaches the Bohai and is located about 104 km away from the river mouth. The Huayuankou station, has a catchment area of 730,036 km^2 (97 per cent of basin total) (Fu et al. 2004). As the lower Yellow River has only a very small local catchment area, differences in discharge at the four gauges reflect mainly diversion of water, attenuation of flows through hydraulic processes and losses from evaporation and infiltration.

Table 17. Lower Yellow River historical mean daily flow data available to this project.

Reach	Gauge	Period of continuous data record	
		Start	End
1. Xiaolangdi to Gaocun	Huayuankou	1/1/1949	31/12/2008
2. Gaocun to Taochengpu	Sunkou	1/1/1952	31/12/2008
3. Taochengpu to estuary	Luokou	1/5/1948	31/12/2008
4. Estuary	Lijin	1/1/1950	31/12/2008

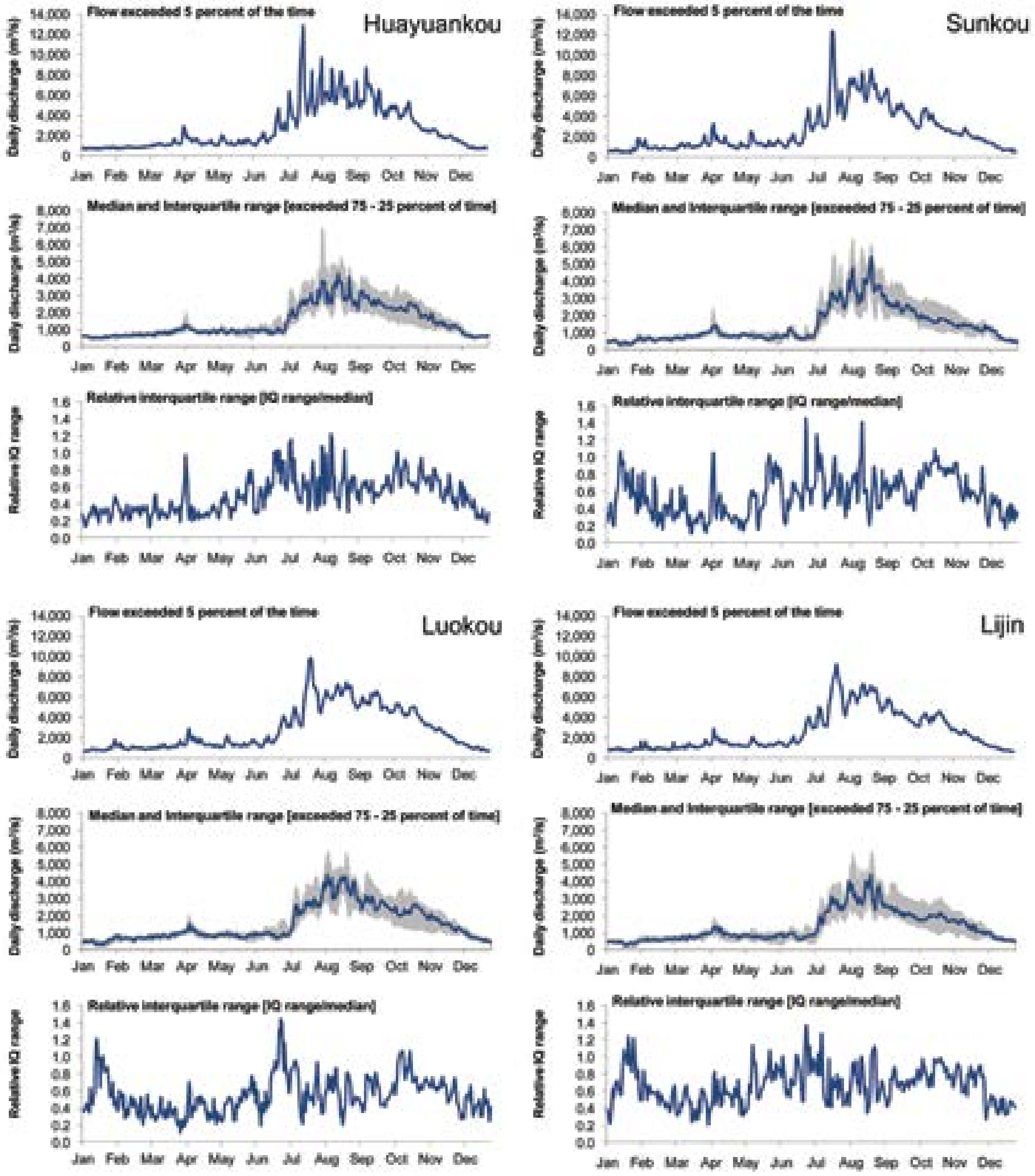
6.6.3 Flow seasonality and water year

The lower Yellow River is characterised by a strongly seasonal flow pattern (Figure 37). The high flows and low flows follow the same seasonal pattern, although the high flows can begin in June, while median flows in June are similar to those in May (Figure 37). Flow variability at Huayuankou gauge is relatively low, although flows are relatively more variable in the high flow season, and in early April. This pattern was not evident at the other gauges (Figure 37).

The water year begins and ends with a low flow month, so that all the water from the high flow season is fully contained within a 12-month period. In this case, the month with the lowest mean discharge may be the ideal start of the water year (Gordon et al. 2004, p. 69). From the perspective of environmental flows, the high flow and low flow seasons are considered to be of equal value, so it is desirable to fully contain the low flow and the following high flow season within a single 12-month period. Thus, for environmental flow studies the water year ideally begins on the first month of the low-flow season. Seasonality was examined in the naturalised monthly flow time series provided by YRCC for Huayuankou and Lijin over the period 1952–2008. The three-month period with the lowest flow was consistently December to February, regardless of the period of record that was analysed (this was also consistent with the pattern of pre-regulation historical daily data depicted in Figure 37). Thus, December to February was designated as the winter season, with December being the start of the water year.

The seasons were also given hydrological descriptors (Table 18). When simplified into two periods the high flow season is June to November and the low flow season is December to May. The same four seasons were adopted by Huang and Zhang (2004) in a hydrological study in the middle Yellow River. The seasons adopted here were for the purposes of environmental flow assessment. Other seasonal divisions have been defined in the literature for other purposes, namely high-flow season 5-months from 1 June to 31 October (Xu 2003), or high-flow season 4-months from 1 July to 31 October (Liu and Zhang 2002; Wang et al. 2005) or June to September (Liu and Zheng 2002). Wang et al. (2010) indicated that the high-flow season for the upper and lower Yellow River was May to July, but this period does not fully cover the natural high flow period.

Figure 37. Statistics calculated for each day of the year for four gauges on the lower Yellow River for the period prior to regulation by Sanmenxia Dam in 1960.



/Note: Flow exceeded 5% of the time is a high flow index, median and interquartile range covers low to mid-sized flows, and relative inter-quartile range is a measure of flow variability.

Table 18. Seasonal divisions adopted for the lower Yellow River.

Months	Season	Hydrological descriptor
December to February	Winter	Cold low flow
March to May	Spring	Snowmelt
June to August	Summer	Warm rising flow
September to November	Autumn	High flow recession

6.6.4 Flow regulation phases

The historical flow series were split into four periods according to the major phases of regulation (Figure 31, Table 19). These periods began in December (start of water year) and ended in November, except for the start of the first period and end of the last period, which were limited by data availability to January and December respectively (Table 19). The water years in which the major dams began operation (signalling the start of a new regulation phase) were not included in the hydrological characterisation, as only part of those 12-month periods were influenced by the new dams.

Table 19. Phases of lower Yellow River flow regulation (based on available flow data) defined for the purpose of hydrological characterisation.

Period	Huayuankou	Sunkou	Luokou	Lijin
Pre-Sanmenxia	1/01/1949– 30/11/1959	1/01/1952– 30/11/1959	1/12/1948– 30/11/1959	1/01/1950– 30/11/1959
Post-Sanmenxia	1/12/1960– 30/11/1985	1/12/1960– 30/11/1985	1/12/1960– 30/11/1985	1/12/1960– 30/11/1985
Post-Longyangxia	1/12/1986– 30/11/1998	1/12/1986– 30/11/1998	1/12/1986– 30/11/1998	1/12/1986– 30/11/1998
Post-Xiaolangdi	1/12/1999– 30/11/2008	1/12/1999– 30/11/2008	1/12/1999– 30/11/2008	1/12/1999– 30/11/2008

6.6.5 Baseflows

The best way to characterise flow components is to first separate them from the flow record, and then undertake statistical description (Gippel 2001). Baseflow is defined as water that enters a river from persistent, slowly varying sources, maintaining streamflow between rainfall events, which contrasts with water that enters a stream or river rapidly, called stormflow, quickflow or event flow. Nathan and McMahon (1990) suggested that a Lyne and Hollick (1979) recursive digital filter was a fast and objective method of continuous baseflow separation:

$$f_k = \alpha f_{k-1} + \beta(1 + \alpha)\,(y_k - y_{k-1})$$

where f_k is the filtered quick response at the k^{th} sampling instant, y_k is the original streamflow, β is filter parameter set to 0.5 and α is a filter parameter set to 0.925. The filtered baseflow then equals y_k - f_k. The algorithm separates baseflow from total stream flow by passing the filter over the stream flow record three consecutive times (forwards, backwards, and forwards again). The justification for the use of this method rests on the fact that filtering out high-frequency signals is intuitively analogous to the separation of low-frequency baseflow from the higher frequencies of quick flow (Nathan and McMahon 1990). Baseflow separation was undertaken using AQUAPAK software (Gordon et al. 2004; the software can be downloaded from http://www.skmconsulting.com).

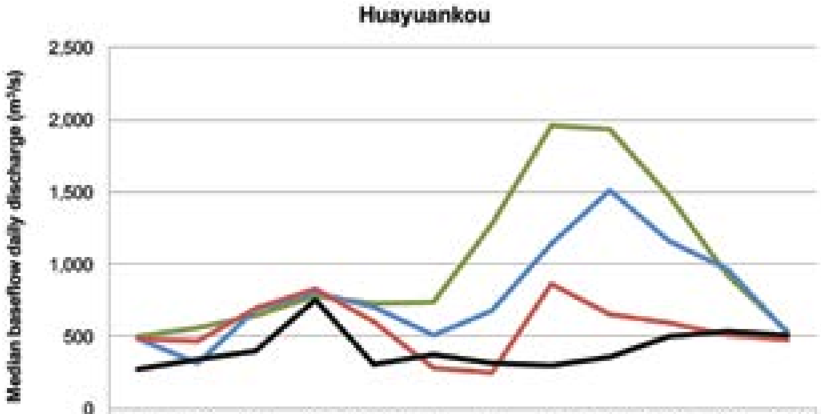
The Baseflow Index (BI) is the ratio of the baseflow component of flow to total flow, such that BI = 1 when flow is all baseflow, and zero when all flow is stormflow. In most streams, the baseflow index is rarely equal to 1 or zero, so most of the time flow comprises a varying mix of baseflow and stormflow. From the perspective of the biota, and in particular with respect to defining flow components that have ecological significance, the total flow in the stream can be said to be strongly baseflow when the baseflow index is close to 1, and in this study a value of BI ≥ 0.9 was used to separate the periods of baseflow from periods that were cease to flow or event flow. This is an arbitrary threshold, and was selected on the basis of expert judgement applied to examination of the Yellow River flow time series.

After separating the periods of baseflow from the time series, these data were sorted by month, and statistics calculated for each month. The median value for each month would be associated with low risk to the environment. Other statistics, such as the 25th percentile and 10th percentile flow, were they to be implemented as minimum flows, would represent higher risk to the environment. Without hydraulic and ecological data, these percentiles have no explicit link to ecological risk, only that the risk increases as the value of baseflow is lower.

Natural monthly baseflows were similar at all four gauges, but the effect of regulation on baseflows varied between gauges (Figure 38, Figure 39, Figure 40 and Figure 41). Each phase of regulation reduced the magnitude of baseflows to a greater degree. At Huayuankou and Sunkou, the impact was mostly during the months June to November (Figure 38 and Figure 39), while at Luokou and Lijin the baseflows were severely reduced in all months except January (Figure 40 and Figure 41). The larger impact at the two downstream gauges reflects withdrawal of water from the river for irrigation. At Sunkou, Luokou and Lijin the post-Xiaolangdi period was characterised by increased baseflows in the months March to July, compared to the previous regulation period (Figure 39, Figure 40 and Figure 41). At Huayuankou, the operation of Xiaolangdi Dam had the effect of reducing baseflows in most months, compared to the previous regulation period (Figure 38).

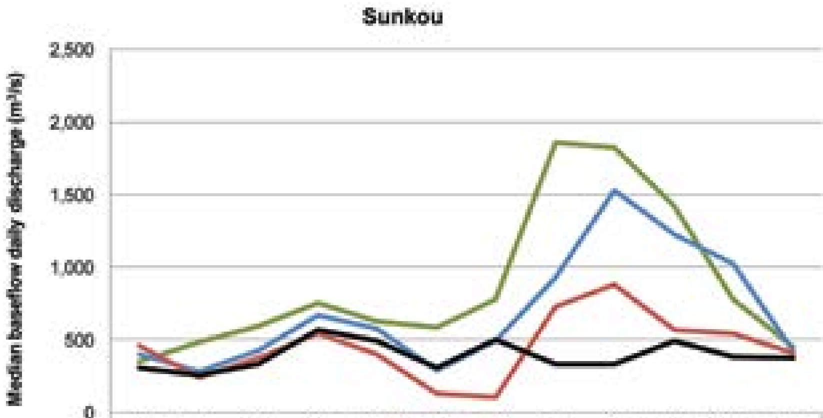
The regulated baseflows in the lower Yellow River are significantly lower than the levels experienced during the pre-Sanmenxia phase. Most of the time they are lower than the 10th percentile of the baseflows experienced in the pre-Sanmenxia phase (Figure 42). This reduction in baseflows could represent a risk to river health.

Figure 38. Statistical definition of baseflow at Huayuankou gauge.



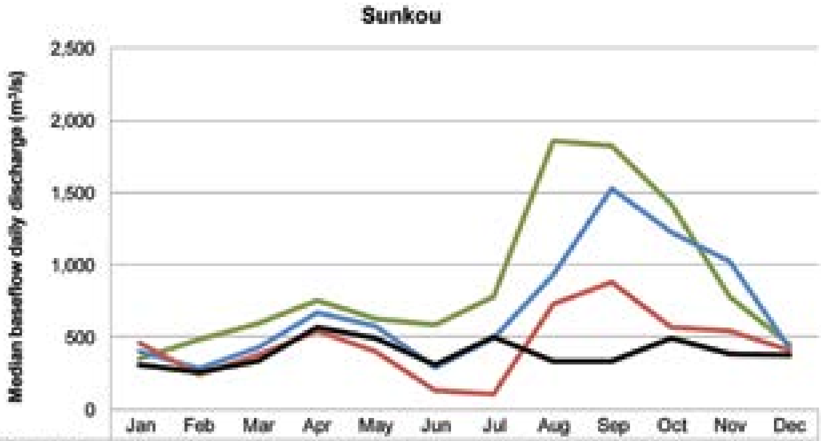
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Pre-Sanmenxia	500	555	640	780	730	735	1,280	1,960	1,930	1,470	918	535
Post-Sanmenxia	482	312	688	803	705	508	673	1,140	1,510	1,155	961	525
Post-Longyangxia	482	466	696	832	604	280	249	859	652	590	512	472
Post-Xiaolangdi	273	343	396	749	305	370	310	299	358	496	537	512

Figure 39. Statistical definition of baseflow at Sunkou gauge.



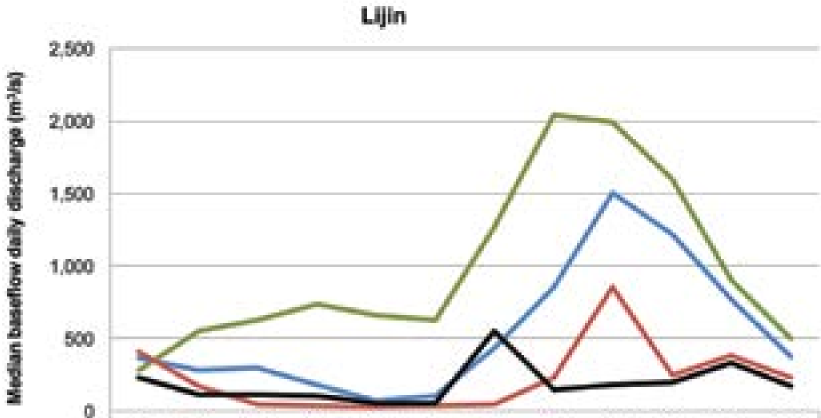
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Pre-Sanmenxia	346	480	596	753	625	580	780	1,860	1,825	1,420	780	445
Post-Sanmenxia	400	276	423	668	573	292	490	930	1,530	1,225	1,020	420
Post-Longyangxia	456	236	370	542	399	131	107	724	881	570	540	407
Post-Xiaolangdi	304	258	328	566	487	307	501	327	331	493	379	372

Figure 40. Statistical definition of baseflow at Luokou gauge.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Pre-Sanmenxia	346	480	596	753	625	580	780	1,860	1,825	1,420	780	445
Post-Sanmenxia	400	276	423	668	573	292	490	930	1,530	1,225	1,020	420
Post-Longyangxia	456	236	370	542	399	131	107	724	881	570	540	407
Post-Xiaolangdi	304	258	328	566	487	307	501	327	331	493	379	372

Figure 41. Statistical definition of baseflow at Lijin gauge.

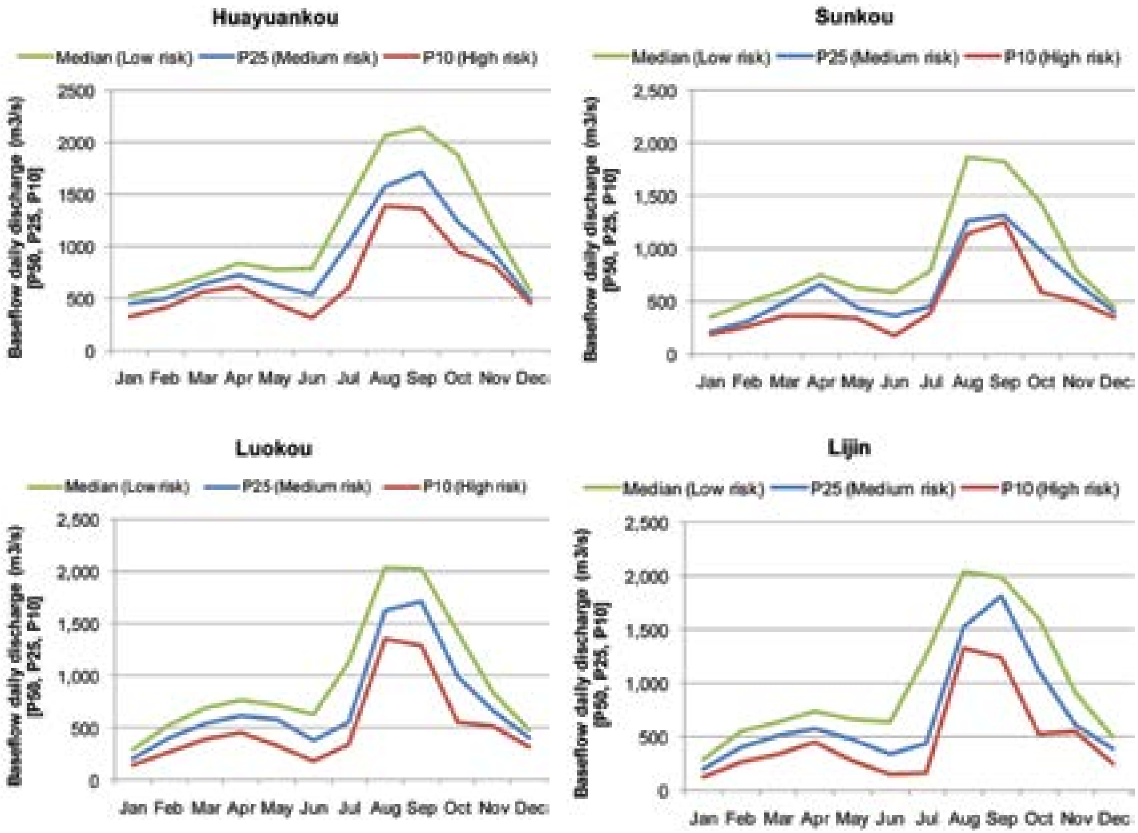


	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Pre-Sanmenxia	280	550	630	740	660	630	1,268	2,040	1,990	1,595	905	500
Post-Sanmenxia	361	284	293	177	67	103	433	857	1,506	1,220	770	372
Post-Longyangxia	408	173	47	35	26	37	43	229	854	249	381	231
Post-Xiaolangdi	228	111	116	102	54	51	548	146	180	192	328	167

6.6.6 Cease to flow events

When the Yellow River stops flowing is known locally as 'duanliu' (Chen et al. 2003), and also as desiccation (Xu 2001), 'no flow' (Ni and Qian 2002; Cao et al. 2008), 'drying up' (Tian and Wang 1997; Liu and Zhang 2002), or 'dry up' (Zhu 2006). Here the term 'cease to flow' (Cui, 2002) is used to describe the hydrological condition when the river stops flowing at a river gauge, but water may remain in pools.

Figure 42. Three statistically defined levels of baseflow based on pre-Sanmenxia historical daily flow data. P25 is 25th percentile, P10 is 10th percentile.



There were successive low flow water years in the periods 1922–1932, 1969–1974 and 1990–1997. From 1922 to 1932, successive droughts occurred as year-long dry periods. Average runoff in this 11-year period was about 70 per cent less than the long- term annual average (Liu and Zheng, 2002). Despite these dry spells, there is no evidence of cease to flow conditions in the lower Yellow River historical flow records for the pre-Sanmenxia period. Thus, cease to flow is not considered to be a natural flow component for the lower Yellow River, and therefore any environmental flow specification should indicate that cease to flow is undesirable.

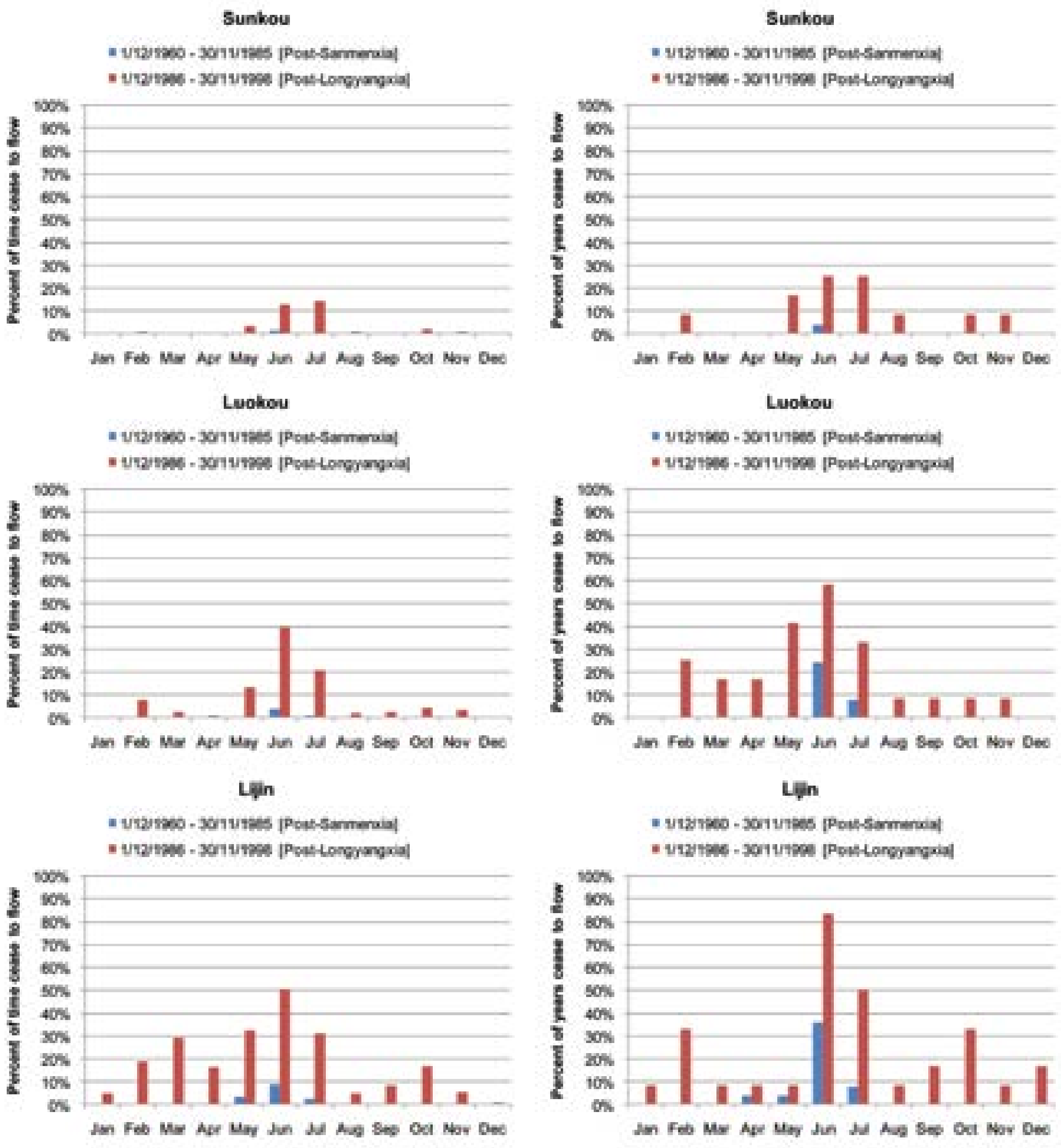
Much has been written about the cease to flow conditions that occurred in the lower Yellow River during the 1970s, 1980s and 1990s (e.g. Tian and Wang 1997; Jiao et al. 1998; Xu, 2001; Cui, 2002; Liu and Zheng, 2002). For example, Xu et al. (2005) summarised the situation as:

> '*In 1972, the Yellow River dried up for the first time in the history of China, and no water flowed into the Bohai Sea over 15 days. From 1985 to 1997, the river dried up nearly every year with the dry period becoming progressively longer. In 1996, the channel in the downstream was dry for 133 days, and it reached 226 days in 1997.*' Liu and Xia (2004) elaborated: '*Moreover, the segment of the river's dried-up channel has continuously extended towards the upper reaches. The length of the dried-up segments in the lower reaches during the 1970s averaged 242 km; this increased to 256 km in the 1980s and 392 km in the 1990s. In 1997, parts of the river dried up almost completely throughout the entire year. According to the hydrological observations at the river estuary, the interruption lasted for 330 days without any freshwater flowing into the sea. In 1997, the dried-up segments of the river course extended upwards to Liuyuankou in Kaifeng City, Henan Province. The length of the dried-up segments was 704 km, accounting for 90% of the river course length in the lower reaches.*'

Apart from two spells of cease to flow in June and December 1960, probably associated with filling of Sanmenxia reservoir and large withdrawls of water from the river during the Great Leap Forward, there were no cease to flow events at Huayuankou in the historical record since 1950. There were no cease to flow events in the lower Yellow River after the operation of Xiaolangdi Dam began. Cease to flow events were apparent in the daily flow records of Sunkou, Luokou and Lijin for the post-Sanmenxia and post-Longyangxia regulation phases (Figure 43). The incidence of cease to flow increased in the downstream direction and was markedly higher in the post-Longyangxia period. The focus of cease to flow was on spring and summer seasons (irrigation supply period), but at Lijin cease to flow occurred in every month. June was particularly affected in the post-Longyangxia period, with cease to flow occurring for 50 per cent of the time, and in 83 per cent of years (Figure 43). At Luokou, only December and January were not affected by cease to flow (Figure 43).

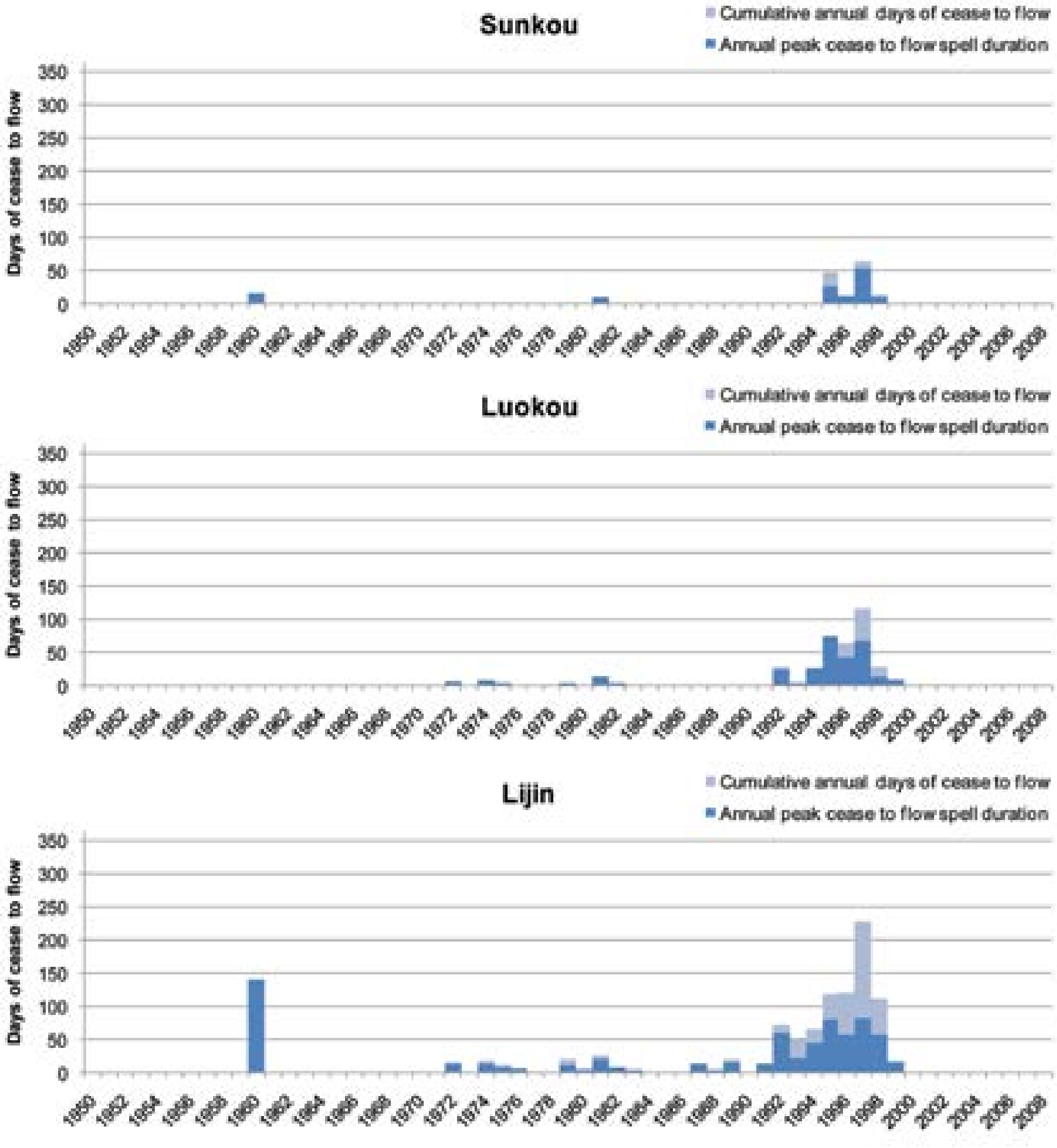
From the ecological health perspective, perhaps the critical aspect of cease to flow duration is the total duration of cease to flow and the duration of the longest cease to flow spell each year. In the lower Yellow River, in years when the river ceased to flow, the majority of the dry days were accounted for in one continuous spell (Figure 44).

Figure 43. Frequency of cease to flow conditions at three gauges on the lower Yellow River for the two regulation periods when cease to flow occurred.



Note that the y-axis is scaled over 365 days, so that the relative lengths of the bars indicate the proportion of the year that the river ceased to flow. Huayuankou is not included as the river did not cease to flow there.

Figure 44. Time series of annual peak duration of cease to flow spell, and total days of cease to flow for each year.



6.6.7 Flow events (pulses and floods)

Flows above baseflow can be described using traditional flood frequency analysis, which predicts the return interval of events of a given magnitude (Gordon et al. 2004, pp. 204–211). In environmental flows assessment, it is usually important to know about the duration and timing of these events, as well as their frequency. The most appropriate analysis for this purpose is spells analysis, which involves selecting a threshold discharge and analysing the frequency, timing and duration characteristics of all the flows above (or below) the threshold (Gordon et al 2004, pp. 218-219). Spells analysis can be performed by AQUAPAK software (Gordon et al. 2004; the software can be downloaded from http://www.skmconsulting.com).

In undertaking spells analysis it is necessary to consider event independence. For example, two spells might occur close together in time, separated by only a minor dip below the discharge threshold. From an ecological, chemical and geomorphological perspective this may not result in any significant disruption to the processes associated with flows above that threshold. In this case, the two spells would not be considered independent, but rather as a single continuous spell. In this study, event independence was defined as requiring a minimum of seven days between instances when discharge exceeded the threshold. This is an arbitrary definition; refinement of this definition would require very detailed research to determine the time period between spells associated with a significant interruption to the processes of interest.

Spells analysis was undertaken across a range of flows from 400 m^3/s to the maximum flow. The discharge range was divided into 50 thresholds, with the equal spacing in the log-transformed range (producing closer spacing, and thus more detail, in the lower flows of the untransformed data range). The spells were characterised for each 3-month season (Table 18) and each regulation phase (Table 19). The spell duration was described by the median, and the spell frequency was described as the mean number of spells per year.

Huayuankou

At Huayuankou, as regulation progressed, the event frequency tended to decline for a given discharge magnitude (Figure 45). For the spring snowmelt season, the pre-Sanmenxia spells were significantly reduced in frequency post-Longyangxia, and further reduced post-Xiaolangdi (Figure 45). In the pre-Sanmenxia period the annual spring snowmelt spell event had a magnitude of 1700 m^3/s. In the post-Longyangxia period this was reduced to 1200 m^3/s (Figure 48). Event duration changed little in this season (Figure 45). In the pre-Sanmenxia period, in the main summer flood season, on average the flow exceeded 900 m^3/s for about 150 days, exceeded 2500 m^3/s for about 17 days, and exceeded 6000–7000 m^3/s for a few days (Figure 45). Regulation severely reduced the frequency and duration of these events. From 2000 onwards the high flows were controlled by Xiaolangdi Dam. Up until 2008 these releases rarely exceeded 4000 m^3/s, with a spell 1000 m^3/s or higher being maintained for about 15 days (Figure 45).

Sunkou

At Sunkou, as regulation progressed, the event frequency tended to decline for a given discharge magnitude across the majority of each season's range and each phase of regulation (Figure 46). For the spring snowmelt season, the pre-Sanmenxia spells were significantly reduced in frequency post-Longyangxia, and further reduced post-Xiaolangdi (Figure 46). In the pre-Sanmenxia period the annual snowmelt spell event had a magnitude of 1600 m^3/s. In the post-Longyangxia period this was reduced to 900 m^3/s (Figure 46). Event duration did not change in a consistent way (Figure 46). In the pre-Sanmenxia period, in the main summer flood season, on average the flow exceeded 900 m^3/s for about 150 days, exceeded 2500 m^3/s for about 20 days, and exceeded 6000–7000 m^3/s for a few days (Figure 46). Regulation severely reduced the frequency and duration of these events. From 2000 onwards the high flows were controlled by Xiaolangdi Dam. Up until 2008 these releases rarely exceeded 3500 m^3/s, with a spell 1000 m^3/s or higher being maintained for about 14 days (Figure 46).

Luokou

At Luokou, as regulation progressed, the event frequency declined for a given discharge magnitude across the majority of each season's range and each phase of regulation (Figure 47). For the spring snowmelt season, the pre-Sanmenxia spells were significantly reduced in frequency post-Longyangxia, and virtually eliminated post-Xiaolangdi (Figure 47). In the pre-Sanmenxia period the annual snowmelt spell event had a magnitude of 1550 m^3/s. In the post-Longyangxia period this was reduced to 800 m^3/s (Figure 47). Event duration did not change by much (Figure 47). In the pre-Sanmenxia period, in the main summer flood season, on average the flow exceeded 900 m^3/s for about 150 days, exceeded 2500 m^3/s for about 10 days, and exceeded 6000 – 7000 m^3/s for a few days (Figure 47). Regulation severely reduced the frequency and duration of these events. From 2000 onwards the high flows were controlled by Xiaolangdi Dam. Up until 2008 these releases rarely exceeded 3500 m^3/s, with a spell 1000 m^3/s or higher being maintained for about 17 days (Figure 47).

Lijin

At Lijin, as regulation progressed, the event frequency declined across the full range of discharge for all seasons (Figure 48). For the spring snowmelt season, the pre-Sanmenxia spells were significantly reduced in frequency post-Longyangxia, and virtually eliminated post-Xiaolangdi (Figure 48). In the pre-Sanmenxia period the annual snowmelt spell event had a magnitude of 1600 m^3/s. In the post-Sanmenxia period this was reduced to 1200 m^3/s, and in the post Longyangxia period this was reduced to 680 m^3/s (Figure 48). In the post Longyangxia period these events also had a much-reduced duration (Figure 48). In the pre-Sanmenxia period, in the main summer flood season, on average the flow exceeded 900 m^3/s for around 150 days, exceeded 2500 m^3/s for about 12 days, and exceeded 5000–6000 m^3/s for a few days (Figure 48). Regulation severely reduced the frequency and duration of these events. From 2000 onwards, the high flows were controlled by Xiaolangdi Dam. Up until 2008 these releases rarely exceeded 3000 m^3/s, with a spell 1000 m^3/s or higher being maintained for about 20 days (Figure 48).

Figure 45. Seasonal frequency and duration of event spells for four phases of regulation at Huayuankou.

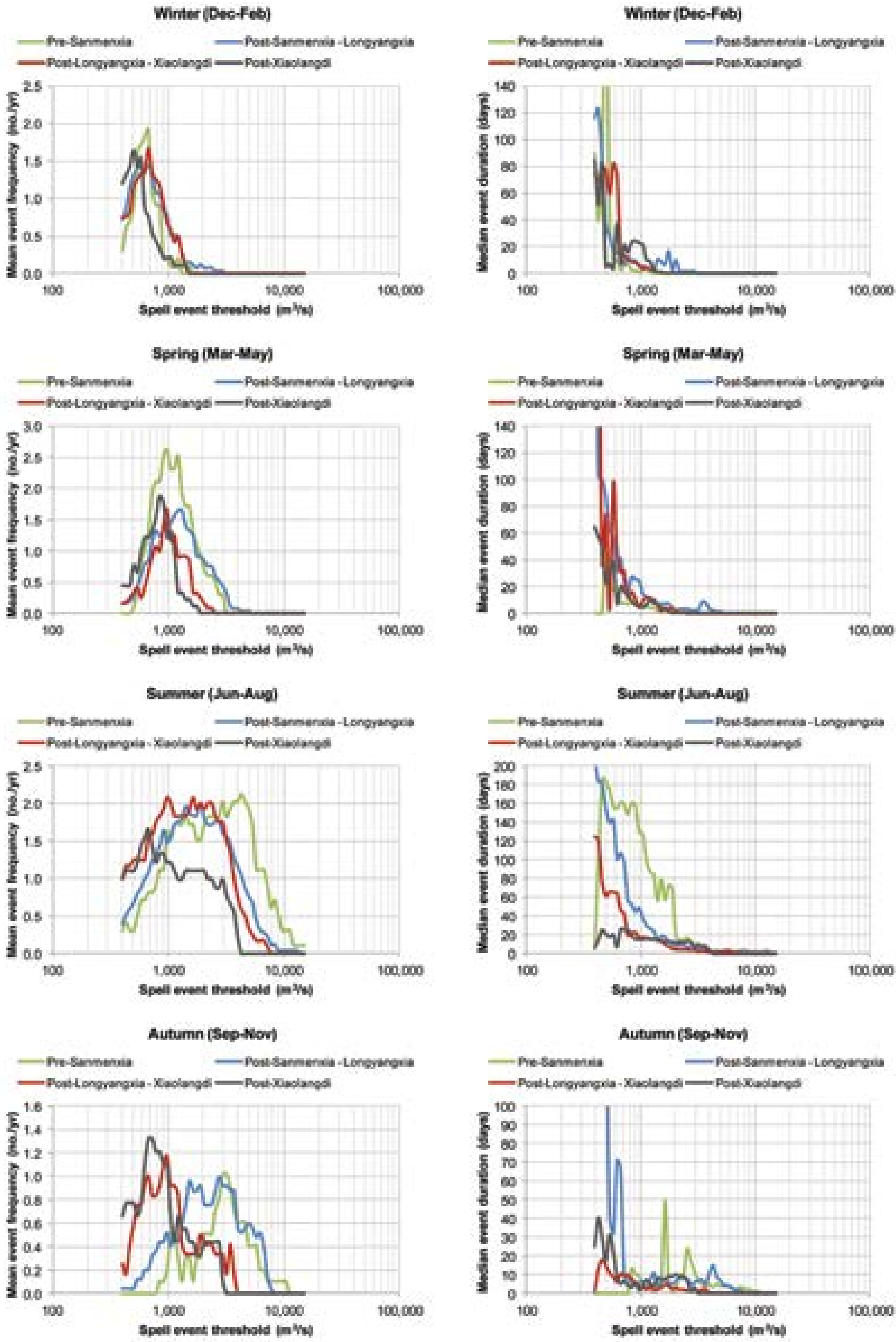


Figure 46. Seasonal frequency and duration of event spells for four phases of regulation at Sunkou.

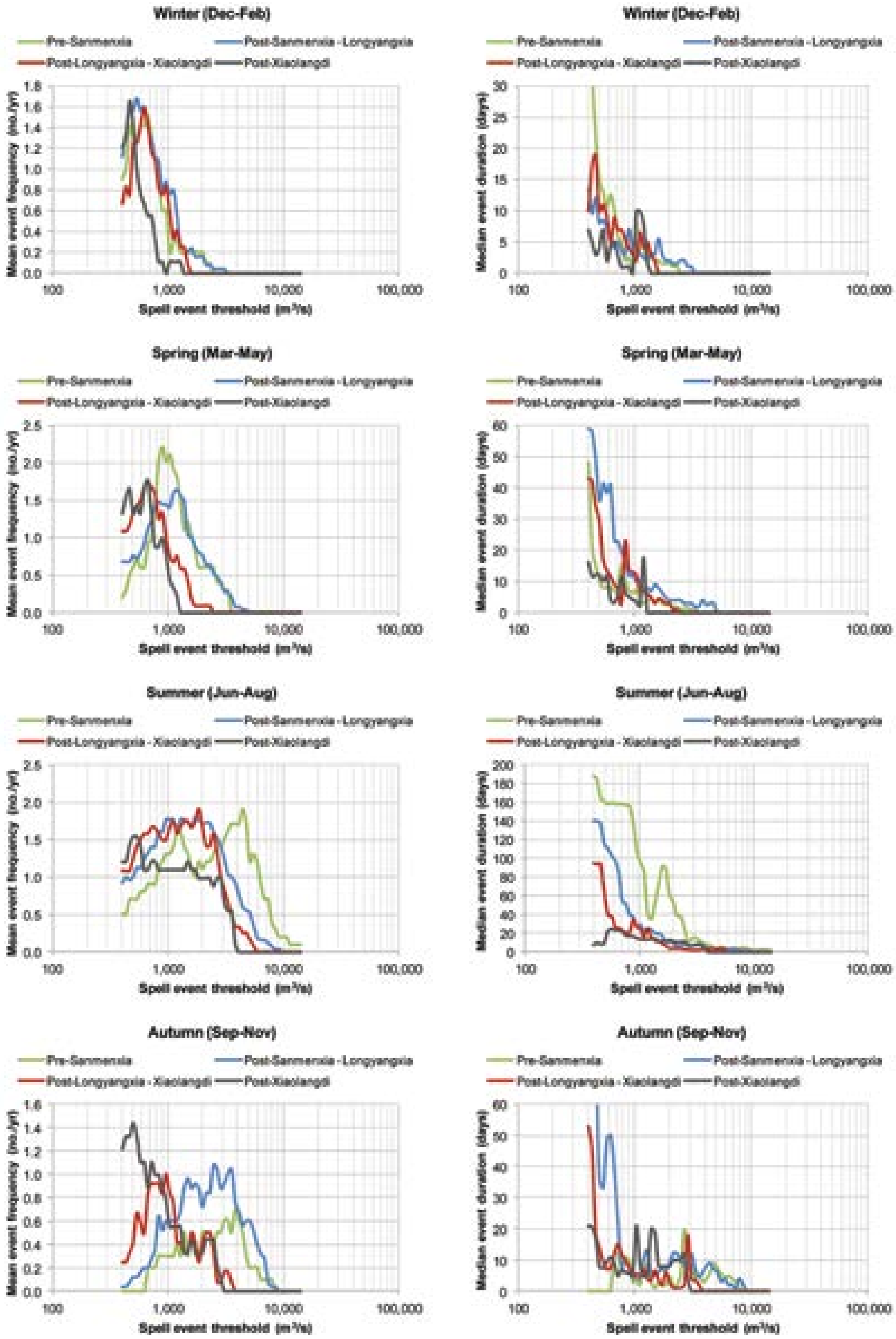


Figure 47. Seasonal frequency and duration of event spells for four phases of regulation at Luokou.

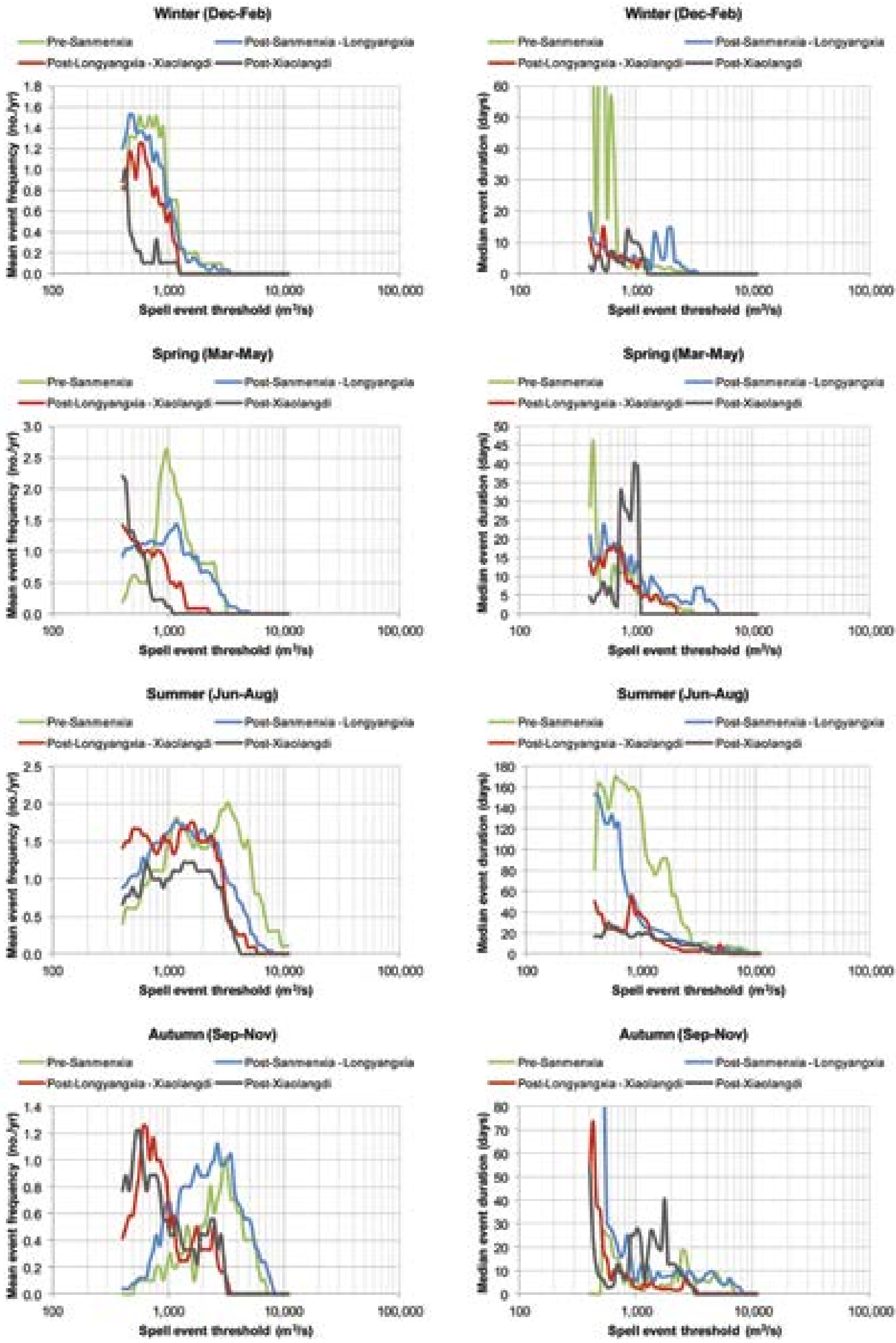
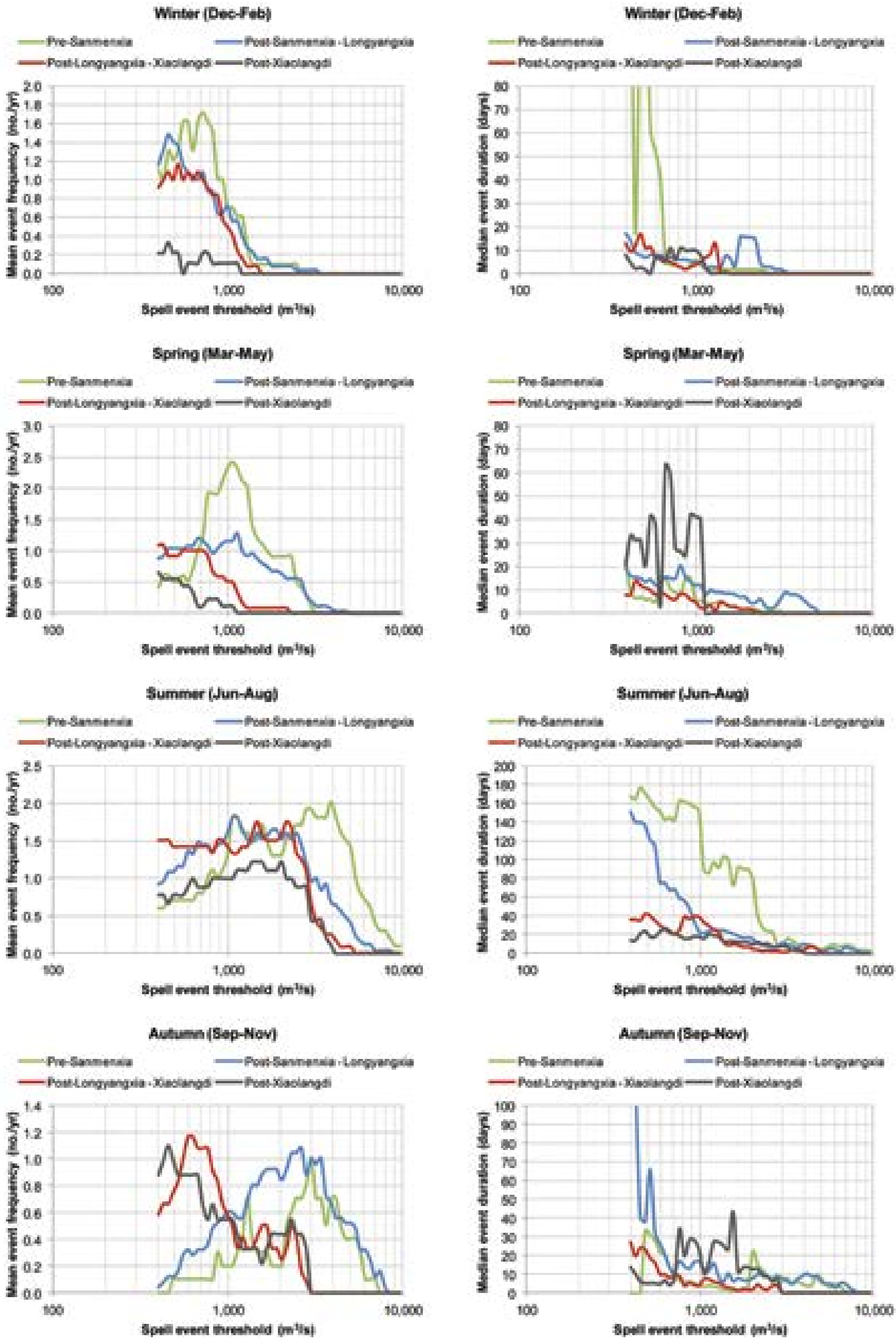


Figure 48. Seasonal frequency and duration of event spells for four phases of regulation at Lijin.



6.6.8 Rates of rise and fall (natural and regulated)

The rates of rise and fall in flow are of interest in environmental flow assessment because some ecological processes are sensitive to these characteristics of the flow regime. For example, a rising river may act as a cue for spawning or migration behaviour, whereas an unnatural rate of rise might not elicit the same response as when the rate of rise lies within the natural range. Some animals seek refuge when flows increase, and an unnaturally rapid rate of rise might not allow sufficient time for them to avoid being washed into fast flow. Rate of fall is also important, as an unnaturally fast rate of fall can cause stranding of animals on the margins of streams, or abandonment of nests by colonial water birds in river-connected wetlands. Excessively high rates of fall can also cause bank slumping (e.g. Thorne 1991).[17]

In regulated rivers, rate of rise and fall is at least partly controllable. From the perspective of minimising water cost, the most efficient way to achieve environmental flow targets is through imposition of rapid rates of rise and fall. This assumes that the rise and fall period does not have a high ecological priority in terms of meeting environmental flow objectives, and because the longer is the rise and fall period, the higher is the volume of water required to provide that flow component. Thus, from the perspective of the sensitivity of ecological processes and efficient use of water, it is the upper limits of rates of rise and fall that are of primary interest. In some cases the ecologically tolerable rates of rise and fall might be known, but in the absence of this knowledge the best guide is the observed rates of rise and fall in the unimpaired flow record. As the main interest is in setting upper limits of rates of rise and fall, the most appropriate statistic is a value higher than the median, but less than the maximum (which would be regarded as an extreme case, and high risk to the biota). In this study the 90th percentile was selected as an arbitrary index of upper rates of rise and fall. Rates of change that occurred infrequently were chosen because it is these infrequent high rates of change that are associated with the onset and initial recession of natural storm events; such conditions provide a guide to the rates of rise and fall that would be acceptable for managed flow event releases from Xiaolangdi Dam.

For each station, rates of rise and fall were characterised across the range of discharge from baseflow to the highest discharge using the 24 discharge classes (equally spaced in the log domain). Within each class, the 90th percentile of rise and fall was calculated. Rates of rise and fall were related to the discharge from which the discharge rose, or fell (i.e. not the discharge to which it rose, or to which it fell).

In the lower Yellow River, the rates of rise and fall are closely related to discharge. The higher the discharge the higher are the rates of rise and fall, with the rates related to discharge by a power function (Figure 49). In general, the rates of rise are faster than rates of recession. The controlled rates of rise in summer WSDR events from Xiaolangdi Dam have mostly been similar to, or less than, the natural rates (as characterised in pre-Sanmenxia phase), but the rates of fall have sometimes been higher than natural rates (Figure 49).

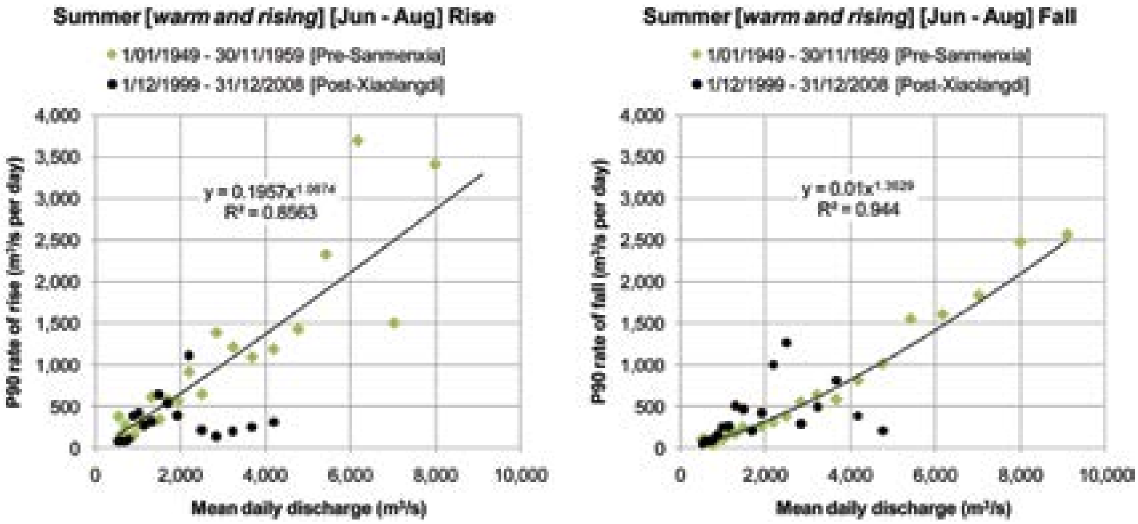
The rate of rise and rate of fall relationships for the four gauging stations were plotted for the four seasons (Figure 50, Figure 51, Figure 52, Figure 53, Figure 54, Figure 55, Figure 56 and Figure 57).

Summary of natural rates of rise and fall

The natural rates of 90th percentile rise and fall (based on pre-Sanmenxia historical data) were described as power functions of discharge, with each relationship significant at $\alpha \le 0.05$ (Table 20). These equations could be used to set the maximum rates of rise and fall for controlled dam releases. Note that as the discharge is increased and decreased over an event cycle, the appropriate rate of rise and fall changes each day.

17 Saturation of river banks under high flow conditions causes the weight of the soil to increase, and the resistance (cohesion and friction) of the soil to reduce. At high flow levels the water in the river exerts a stabilizing pressure on the bank slope. The stabilising pressure is lost when the river level drops during flood recession. If the water level drops so rapidly that the pore pressures within the slope do not have time to change in equilibrium with the drop in external water level, the risk of bank failure will increase significantly. This type of failure is known as rapid drawdown failure. High permeability materials (such as sands and gravels) can drain during rapid drawdown, but low permeability materials (clays and silts) do not. Thus, drawdown failure is typically a problem associated with fine-grained bank materials (see Thorne 1991).

Figure 49. Distribution of 90th percentile rates of rise and fall for the high-flow season rising phase (summer) and recession phase (autumn) for the pre-Sanmenxia and post-Xiaolangdi phases of regulation at Huayuankou.



Note: Discharge values represent data grouped within classes.

Table 20. Relationships describing the 90th percentile rates of rise and fall as a function of discharge in the pre-Sanmenxia phase for four gauging stations on the lower Yellow River.

Station	Season	Rate of rise (R) as function of discharge (Q) (m^3/s per day)	Rate of fall (F) as function of discharge (Q) (m^3/s per day)
Huayuankou	Winter (Dec–Feb)	$R = 0.0537\ Q^{1.2475}$	$F = 0.0164\ Q^{1.3234}$
	Spring (Mar–May)	$R = 1.1492\ Q^{0.7899}$	$F = 0.0088\ Q^{1.4223}$
	Summer (June–Aug)	$R = 0.6217\ Q^{0.9896}$	$F = 0.0213\ Q^{1.3050}$
	Autumn (Sep–Nov)	$R = 0.0343\ Q^{1.2159}$	$F = 0.0298\ Q^{1.2010}$
Sunkou	Winter (Dec–Feb)	$R = 0.5291\ Q^{0.9287}$	$F = 0.1483\ Q^{1.0373}$
	Spring (Mar–May)	$R = 2.1203\ Q^{0.6997}$	$F = 0.0977\ Q^{1.1076}$
	Summer (June–Aug)	$R = 1.3171\ Q^{0.8482}$	$F = 0.0299\ Q^{1.2482}$
	Autumn (Sep–Nov)	$R = 1.6009\ Q^{0.6931}$	$F = 1.1031\ Q^{0.7333}$
Luokou	Winter (Dec–Feb)	$R = 1.6039\ Q^{0.7506}$	$F = 0.2863\ Q^{0.9331}$
	Spring (Mar–May)	$R = 0.0766\ Q^{1.2342}$	$F = 0.0909\ Q^{1.1171}$
	Summer (June–Aug)	$R = 2.6654\ Q^{0.7136}$	$F = 0.0909\ Q^{1.0793}$
	Autumn (Sep–Nov)	$R = 5.0790\ Q^{0.5338}$	$F = 0.2265\ Q^{0.9221}$
Lijin	Winter (Dec–Feb)	$R = 3.5291\ Q^{0.6375}$	$F = 0.1835\ Q^{0.9915}$
	Spring (Mar–May)	$R = 10.749\ Q^{0.4610}$	$F = 0.0197\ Q^{1.3413}$
	Summer (June–Aug)	$R = 5.5310\ Q^{0.6078}$	$F = 0.0996\ Q^{1.0720}$
	Autumn (Sep–Nov)	$R = 2.7810\ Q^{0.6121}$	$F = 0.1520\ Q^{0.9820}$

Figure 50. Distribution of 90th percentile rates of rise for four phases of regulation at Huayuankou.

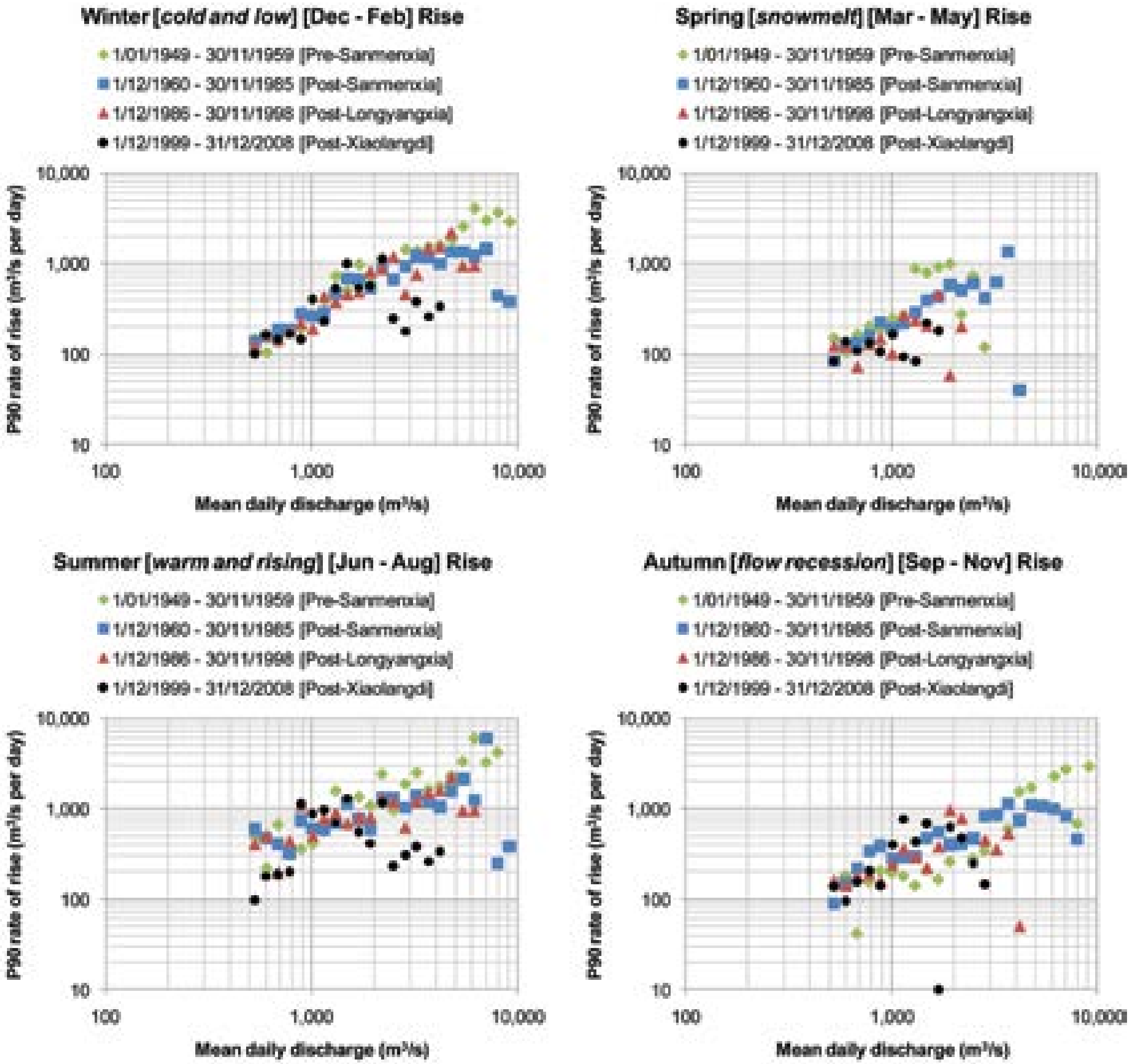


Figure 51. Distribution of 90th percentile rates of fall for four phases of regulation at Huayuankou.

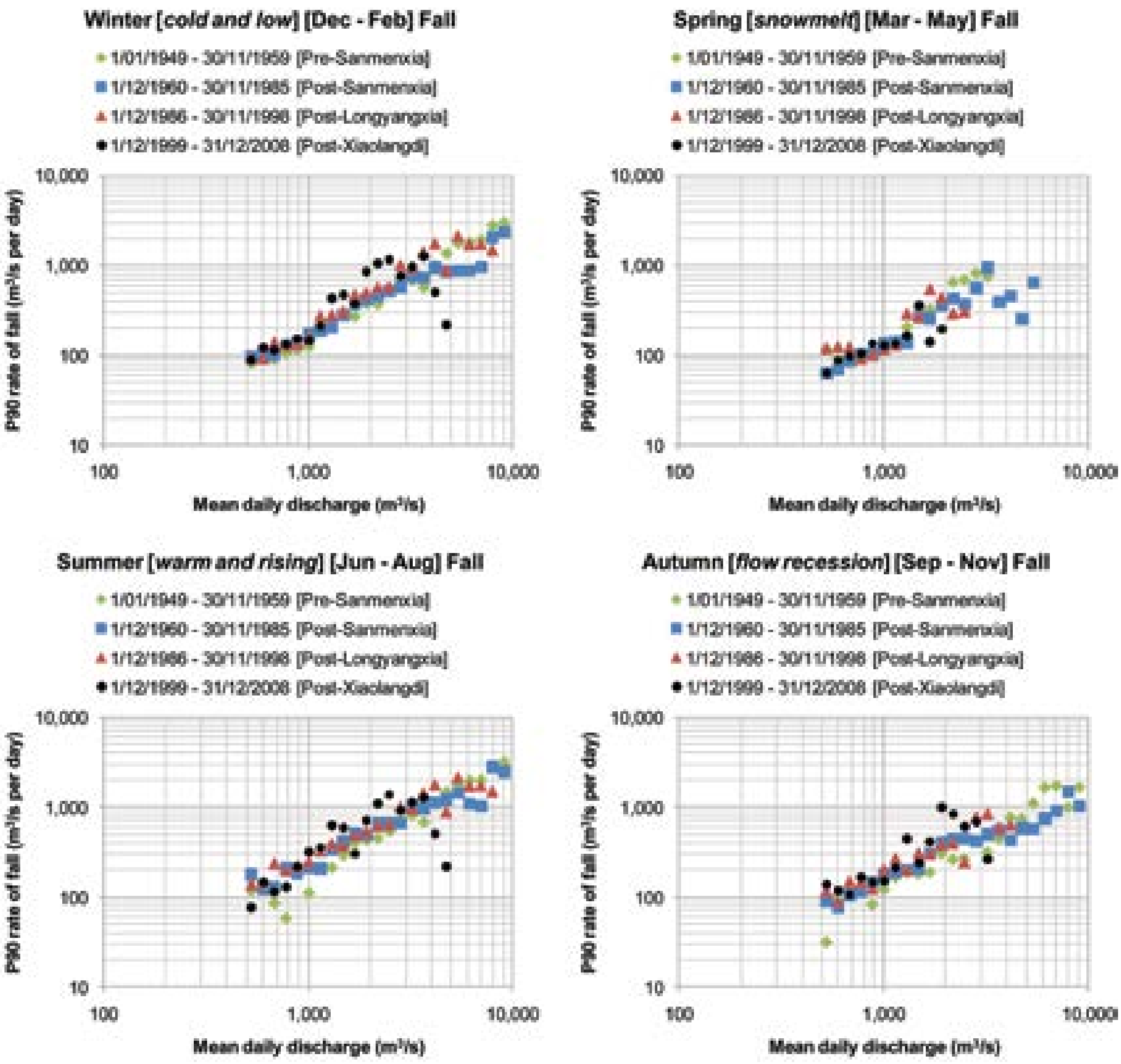


Figure 52. Distribution of 90th percentile rates of rise for four phases of regulation at Sunkou.

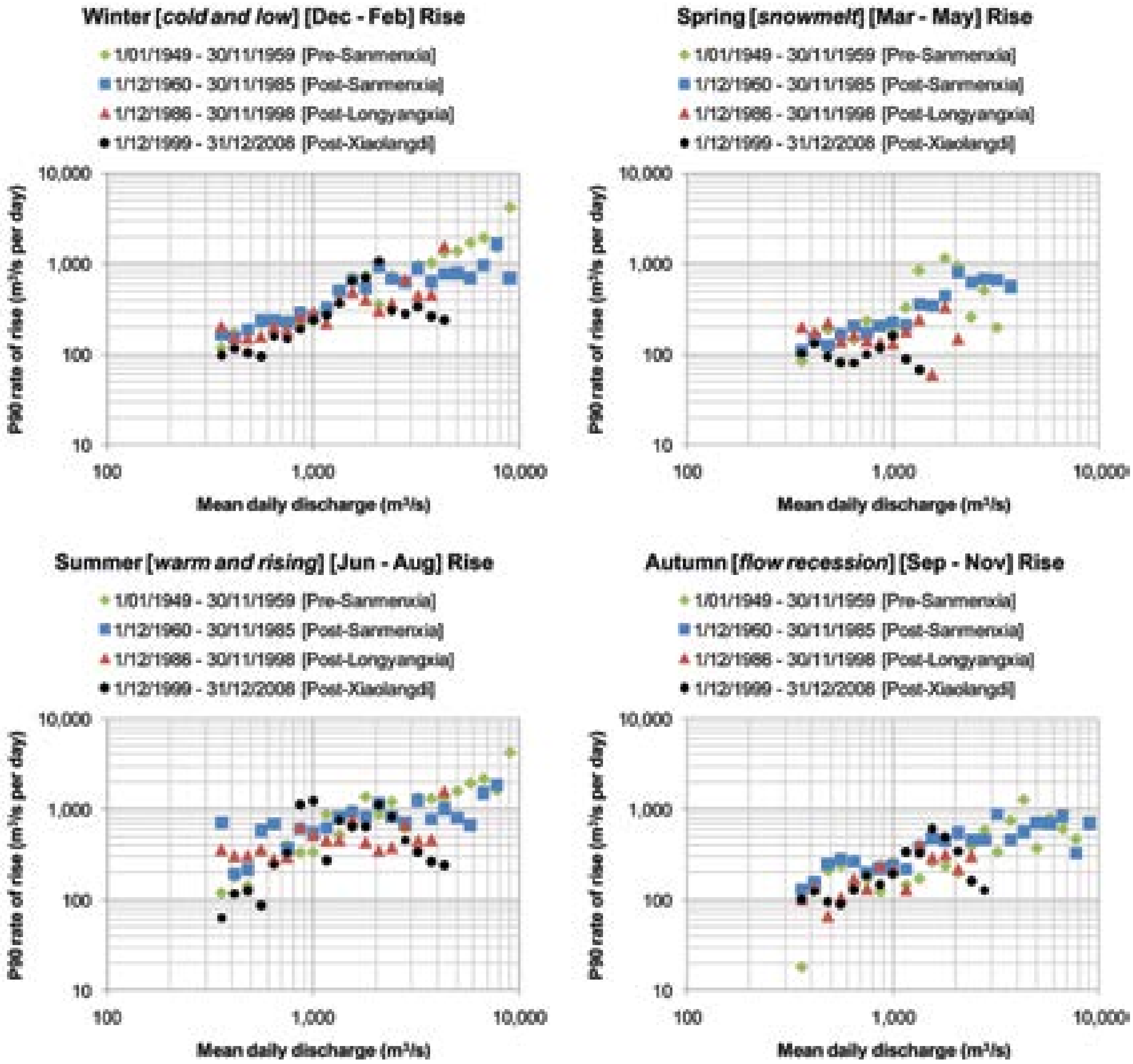


Figure 53. Distribution of 90th percentile rates of fall for four phases of regulation at Sunkou.

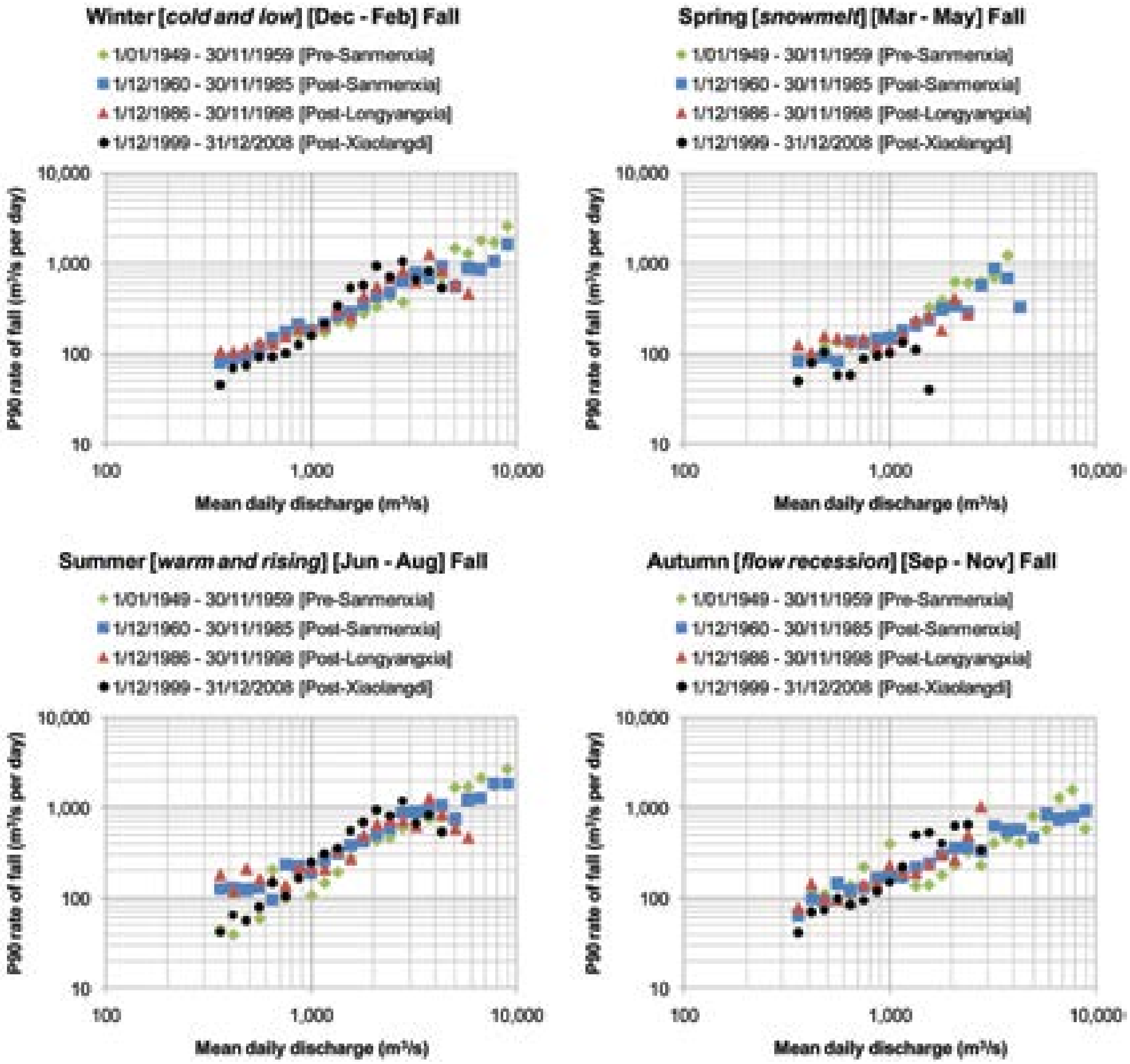


Figure 54. Distribution of 90th percentile rates of rise for four phases of regulation at Luokou.

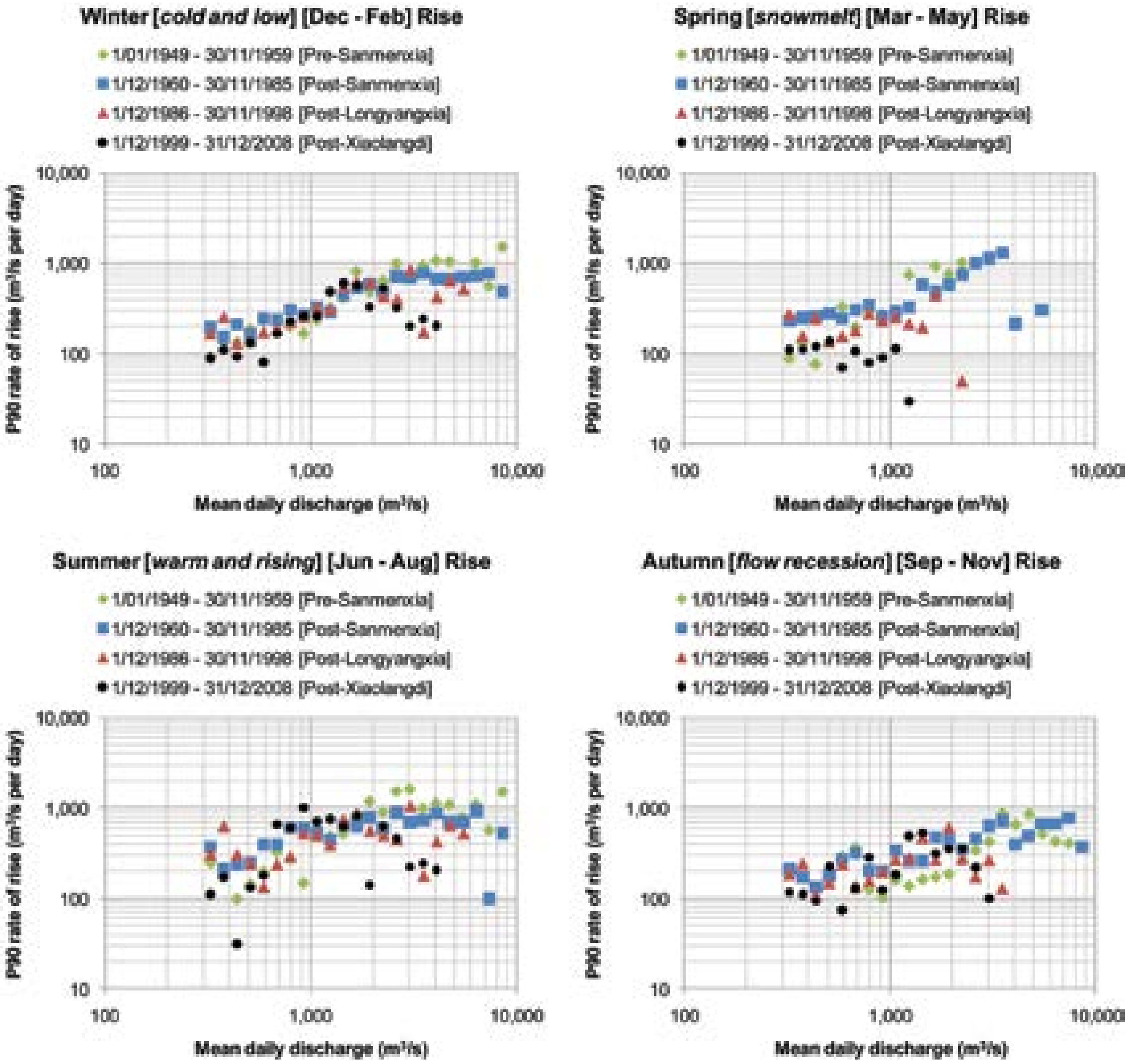


Figure 55. Distribution of 90th percentile rates of fall for four phases of regulation at Luokou.

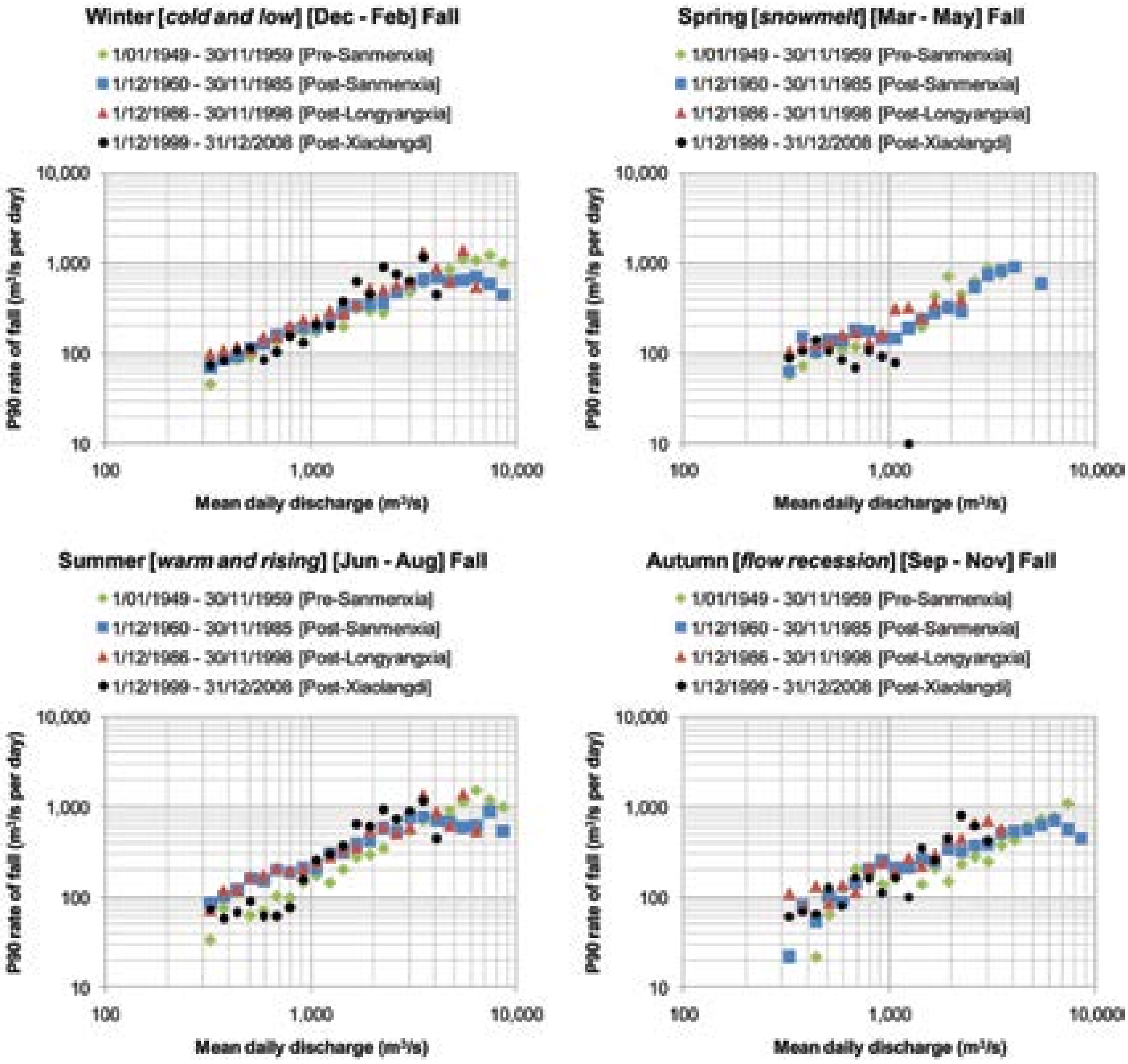


Figure 56. Distribution of 90th percentile rates of rise for four phases of regulation at Lijin.

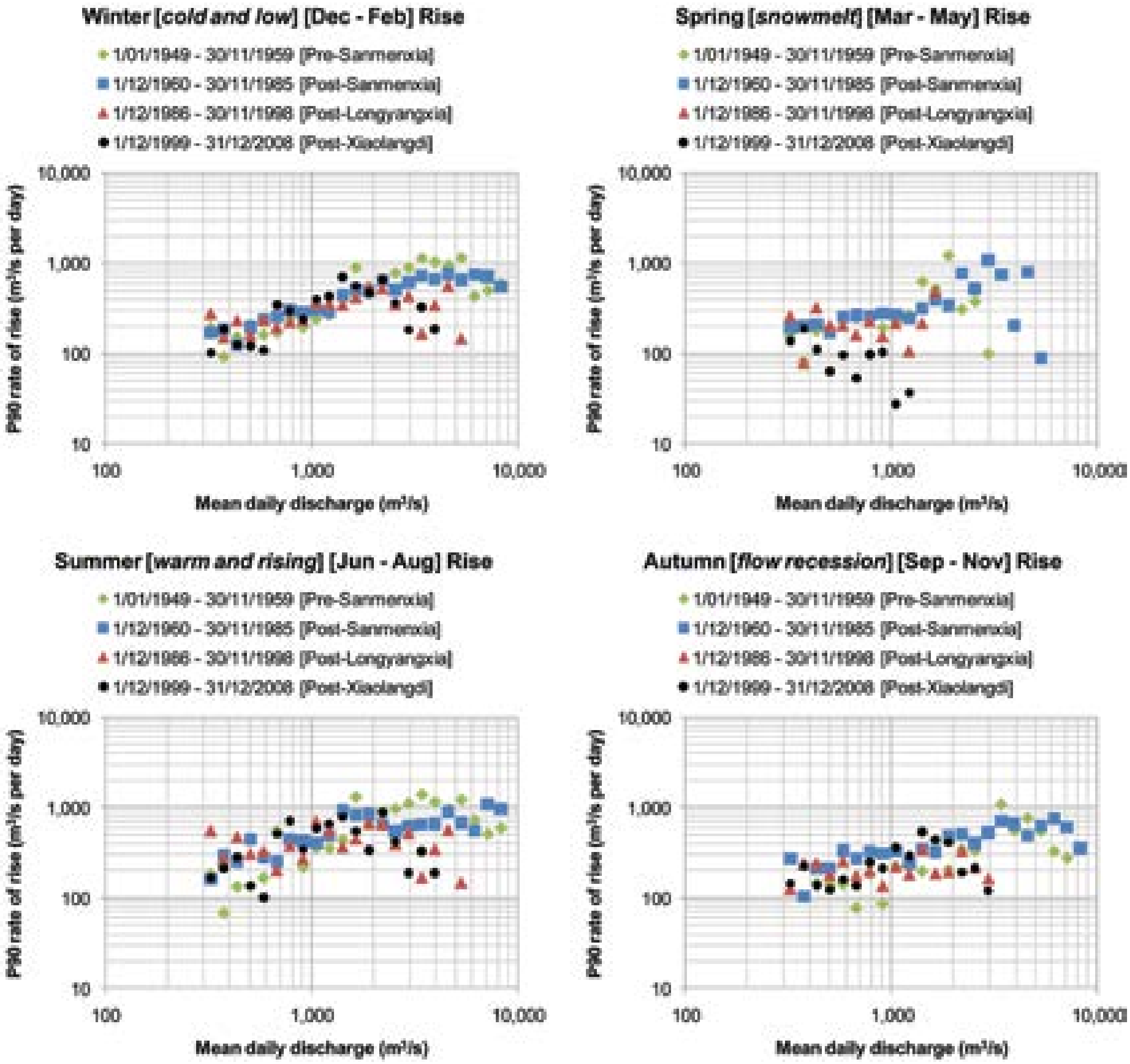
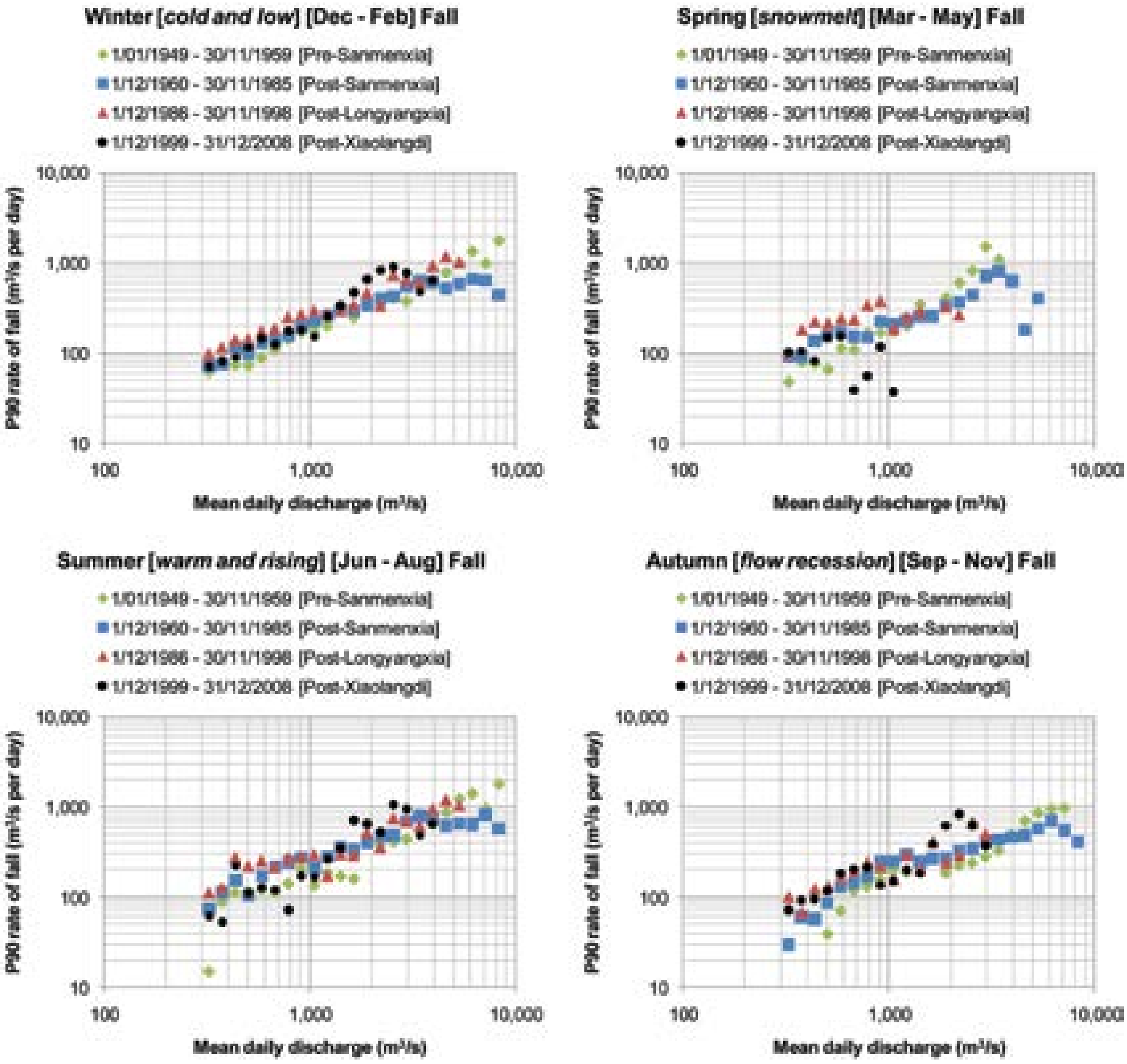


Figure 57. Distribution of 90th percentile rates of fall for four phases of regulation at Lijin.

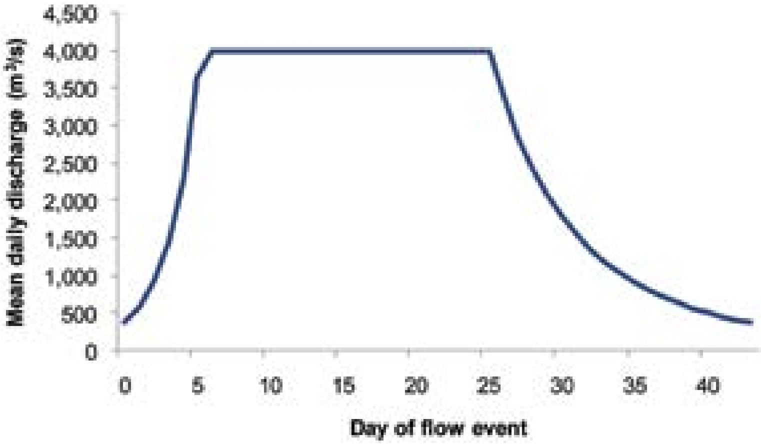


Application of rates of rise and fall relationships

If a hypothetical WSDR event is released from Xiaolangdi Dam in June with the target being 20 days sustained flow at 4000 m³/s, assuming the event rises from and falls to the existing baseflow of 370 m³/s (the median June baseflow – see Figure 38), the Huayuankou summer rate of rise equation is used for the rising limb (Table 20), and the Huayuankou autumn rate of rise equation is used for the falling limb (Table 20). The autumn rate of fall is recommended here because this event is simulating the natural wet season flood, which prior to regulation would have receded in autumn (Figure 37). The resulting hydrograph (Figure 58) had a duration of 43 days; the peak was reached in just over 5 days and used 0.8×10^9 m³; the peak used 6.9×10^9 m³; the recession lasted for 18 days and used 2.0×10^9 m³; and the total discharge for the event was 9.7×10^9 m³. Had baseflow applied for this period, the total water used would have been 1.4×10^9 m³, so the water used in implementing the event, compared to not implementing the event, was 8.3×10^9 m³.

The above example application of the rates of rise and fall relationships derived from the natural hydrology is for a WSDR event. However, these relationships can be applied to any release from Xiaolangdi Dam. It is likely that the rates of rise and fall for events need only be prescribed on the basis of the requirements at Huayuankou, as normal attenuation will ensure that the rates of rise and fall further downstream are within acceptable limits. The exception is if large volumes of water are diverted from the river through sluices. The sluices should be opened and closed so as to avoid excessive rates of change in flow in the lower Yellow River.

Figure 58. Hydrograph of hypothetical June sediment flushing event at 4000 m3/s for 20 days with appropriate rates of rise and fall. Rates of rise and fall under operation of Xiaolangdi Dam.



Note: In this example, the entire event has a duration of 43 days if it rises from, and falls to, a baseflow of 370 m^3/s.

6.6.9 Rates of rise and fall under operation of Xiaolangdi Dam

Since Xiaolangdi Dam was completed in October 1999, the flow in the lower Yellow river has come under much tighter control. The dam has an associated hydropower plant; operation of such plants usually involves frequent and rapid changes in discharge according to electricity demand. The changes can occur at the sub-daily scale (hydro-peaking – usually twice daily fluctuations) or at the daily and seasonal scale. Sub-daily flow data were not available to this project, so the analysis was limited to investigation of changes at the daily time-step.

The natural rates of 90th percentile rise and fall (based on pre-Sanmenxia historical data) (Table 20) were adopted as the standard for maximum desirable rates for good river health. The observed daily rates of rise and fall over the period 2000–2008 were compared with this standard. For each day when flow was higher than the post-Xiaolangdi median baseflow for each month (Figure 38, Figure 39, Figure 40 and Figure 41), the maximum rate suggested by this standard (the expected, E) was calculated (as a function of the discharge) and then compared against the actual change in discharge (the Observed, O). The O/E ratio was then calculated. A ratio of O/E less than or equal to 1 meant that the rate of rise or fall was less than or equal to the standard.

At Huayuankou the rates of rise exceeded the standard for good river health 10 per cent of the time (expected is 10 per cent) and the rates of fall exceeded the standard 19 per cent of the time (expected is 10 per cent). The rates of rise and fall exceeded that of the standards by a factor of 2 for 3.5 per cent and 3.8 per cent of the time respectively. In comparison, for the pre-Sanmenxia phase, rates of rise and fall exceeded the standards by a factor of 2 for 3.0 per cent and 0.3 per cent of the time respectively. Post-Xiaolangdi rates of rise and fall with O/E greater than 1 were distributed across the full range of discharge, although the majority of instances were associated with flows less than 1000 m^3/s (Figure 59). Under the post-Xiaolangdi regime, high rates of rise and fall occurred in all months; in the low flow winter season, flow events above baseflow were not common, so there was low potential for high rates of rise or fall. It is apparent that relatively high rates of rise and fall were associated with the annual WSDR events.

At Sunkou the rates of rise exceeded the standard for good river health 9 per cent of the time (expected is 10 per cent) and the rates of fall exceeded the standard 10 per cent of the time (expected is 10 per cent). The rates of rise and fall exceeded that of the standards by a factor of 2 for 2.3 per cent and 2.0 per cent of the time respectively. In comparison, for the pre-Sanmenxia phase, rates of rise and fall exceeded the standards by a factor of 2 for 4.1 per cent and 0.6 per cent of the time respectively. Post-Xiaolangdi Dam, rates of rise and fall with O/E greater than 1 were distributed across the full range of discharge (Figure 60). In comparison, under the pre-Sanmenxia phase, rates of rise and fall with O/E greater than 1 were more evenly distributed across the discharge range. Under the post-Xiaolangdi regime, high rates of rise and fall occurred in all months; in the low flow winter season, flow events above baseflow were not common, so there was low potential for high rates of rise or fall. It is apparent that relatively high rates of rise and fall were associated with the annual WSDR events.

At Luokou the rates of rise exceeded the standard for good river health 11 per cent of the time (expected is 10 per cent) and the rates of fall exceeded the standard 12 per cent of the time (expected is 10 per cent). The rates of rise and fall exceeded that of the standards by a factor of 2 for 2.7 per cent and 3.4 per cent of the time respectively. In comparison, for the pre-Sanmenxia phase, rates of rise and fall exceeded the standards by a factor of 2 for 3.0 per cent and 0.6 per cent of the time respectively. Post-Xiaolangdi rates of rise and fall with O/E greater than 1 were distributed across the full discharge range (Figure 60). In comparison, under the pre-Sanmenxia phase, rates of rise and fall with O/E greater than 1 were more evenly distributed across the discharge range. Under the post-Xiaolangdi regime, high rates of rise and fall occurred in all months; in the low flow winter season, flow events above baseflow were not common, so there was low potential for high rates of rise or fall. It is apparent that relatively high rates of rise and fall were associated with the annual WSDR events.

At Lijin the rates of rise exceeded the standard for good river health 10 per cent of the time (expected is 10 per cent) and the rates of fall exceeded the standard 24 per cent of the time (expected is 10 per cent). The rates of rise and fall exceeded that of the standards by a factor of 2 for 3.3 per cent and 7.6 per cent of the time respectively. In comparison, for the pre-Sanmenxia phase, rates of rise and fall exceeded the standards by a factor of 2 for 3.3 per cent and 0.7 per cent of the time respectively. Post-Xiaolangdi Dam, rates of rise and fall with O/E greater than 1 were distributed across the full range of discharge, although the majority of instances of high rates of fall were associated with flows less than 1000 m^3/s (Figure 62). In comparison, under the pre-Sanmenxia phase, rates of rise and fall with O/E greater than 1 were more evenly distributed across the discharge range. Under the post-Xiaolangdi regime, high rates of rise and fall occurred in all months; in the low flow winter season, flow events above baseflow were not common, so there was low potential for high rates of rise or fall. It is apparent that relatively high rates of rise and fall were associated with the annual WSDR events.

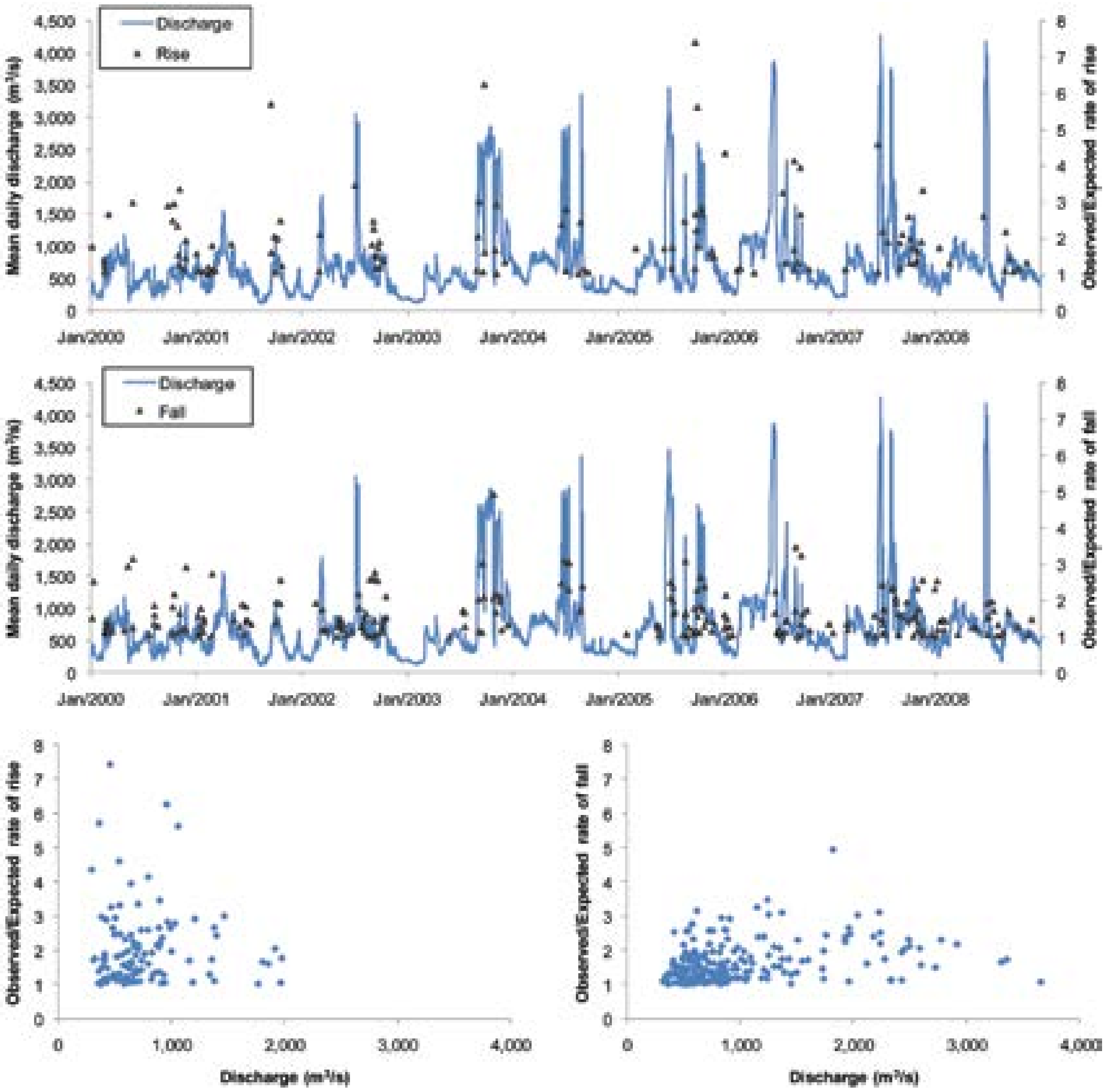
The peak rates of rise and fall associated with the annual WSDR events were significantly higher than the adopted standard for good river health, except for the 2006 event (Figure 63). The peak rates of rise were up to 5 times higher than the standard and the peak rates of fall were 2 to 3 times higher than the standard for all events. Such rates of rise and fall were not typical of events of this scale during the pre-Sanmenxia phase; for flow events rising from flows in the range 300–2000 m^3/s the maximum recorded O/E values for rate of rise were 3.1, 4.6, 5.5, and 6.0 for Hyauyuankou, Sunkou, Luoku and Lijin respectively; for flow events falling from flows in the range 2000–5000 m^3/s the maximum O/E values for rate of fall were 1.6, 1.8, 2.7, and 2.1 for Hyauyuankou, Sunkou, Luokou and Lijin respectively. So, the rates of rise and fall of some of the WSDR events are close to the maximum natural rates, especially for rate of fall. It is apparent that the operators open and shut-down these dam release events rapidly (often over one or two days), which satisfies the objective of minimising total event water use, or maximising sediment transfer efficiency. The hydraulic efficiency of the lower Yellow River is evident in the lack of attenuation of the high rates of rise and fall in the downstream direction (in fact, peak O/E rates were often higher at the downstream gauging stations) (Figure 63).

While most of the WSDR events have been delivered with higher than natural rates of rise and fall, it is also the case that since Xiaolangdi began operation, some natural rainfall-induced events have had higher than pre-dam rates of rise and fall. Under pre-dam conditions, when a rainstorm occurred in the lower Yellow River catchment, the rapid inflow from tributaries would often have merged with a much higher flow in the mainstem, so local inflows would have had only a modest influence on the hydrology of the mainstem. After regulation, the flow in the mainstem has tended to be lower, so tributary storm flows can have a stronger influence on the hydrology of the mainstem. Thus, the tributary inflows impose their naturally high rates of rise and fall (which are typical of smaller streams) on the mainstem of the Yellow River.

Apart from WSDR events and natural tributary inflow events, a third potential source of higher than natural rates of fall is the opening of sluice gates to abstract water from the river. The period of main irrigation demand in the lower Yellow River begins in April and runs to June (Chen et al. 2009). High rates of fall were apparent in this season, but data are not readily available to test whether sluice gate operation was a significant contributor.

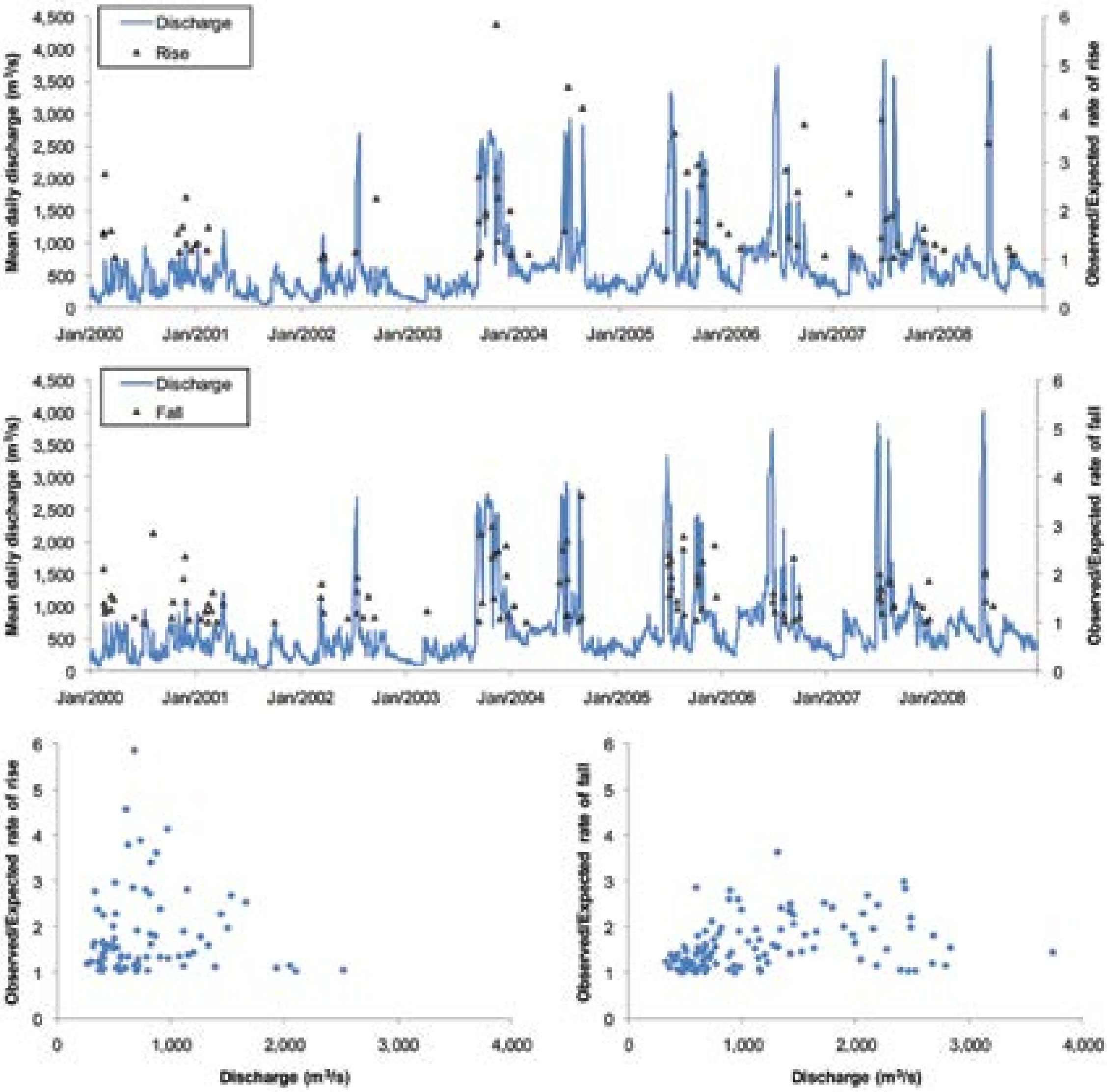
A fourth potential source of higher than natural rates of rise and fall is rapidly changing hydro-power plant releases. Suitable data to investigate this aspect of Xiaolangdi Dam operation were not available to this project.

Figure 59. Mean daily discharge hydrograph at Huayuankou for the period 2000 to 2006 (post-Xiaolangdi Dam), showing the O/E 90th percentile rates of rise and fall for O/E values exceeding 1.



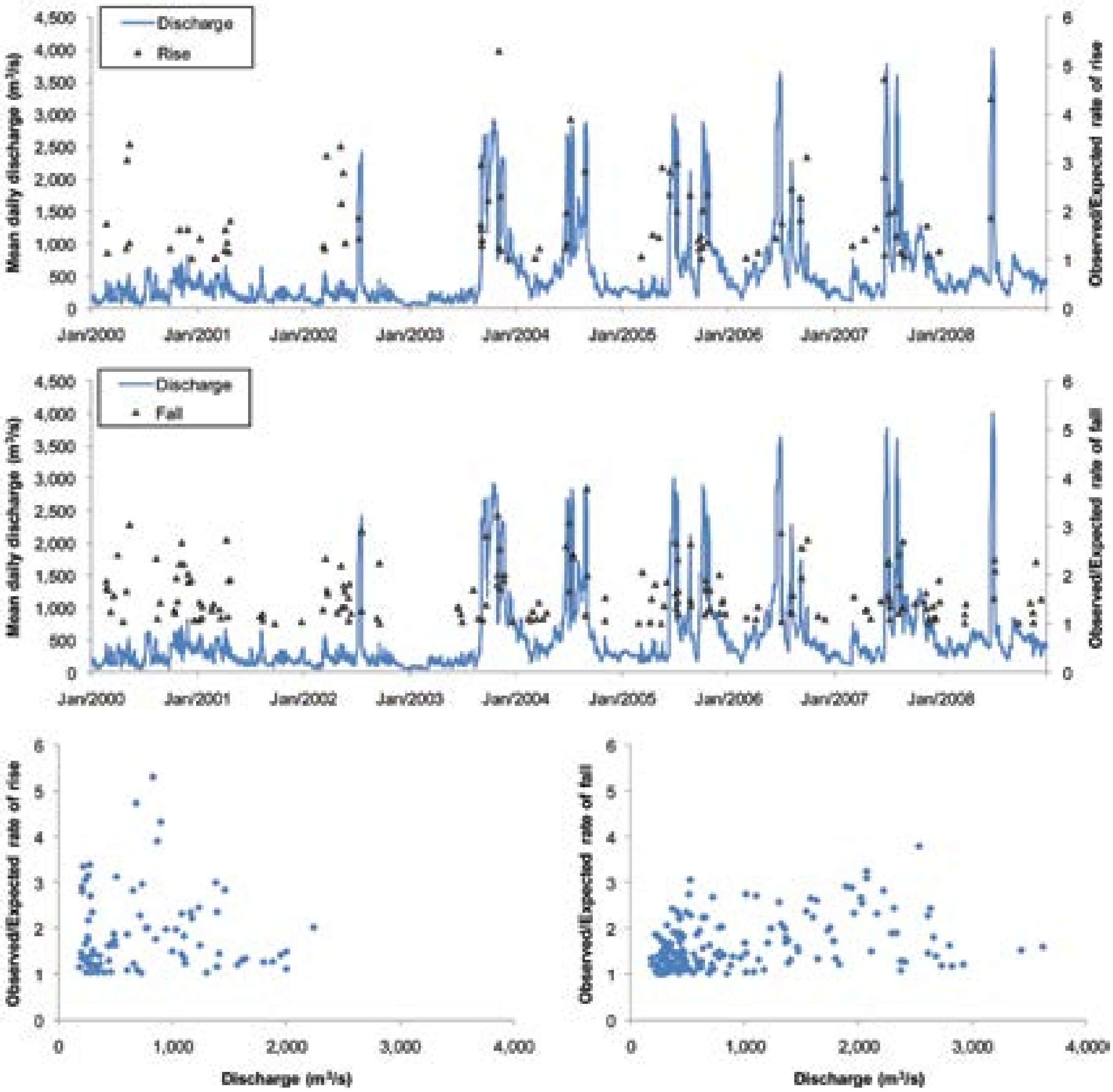
Note: Lower figures plot the same data in scattergraph form.

Figure 60. Mean daily discharge hydrograph at Sunkou for the period 2000 to 2006 (post-Xiaolangdi Dam), showing the O/E 90th percentile rates of rise and fall for O/E values exceeding 1.



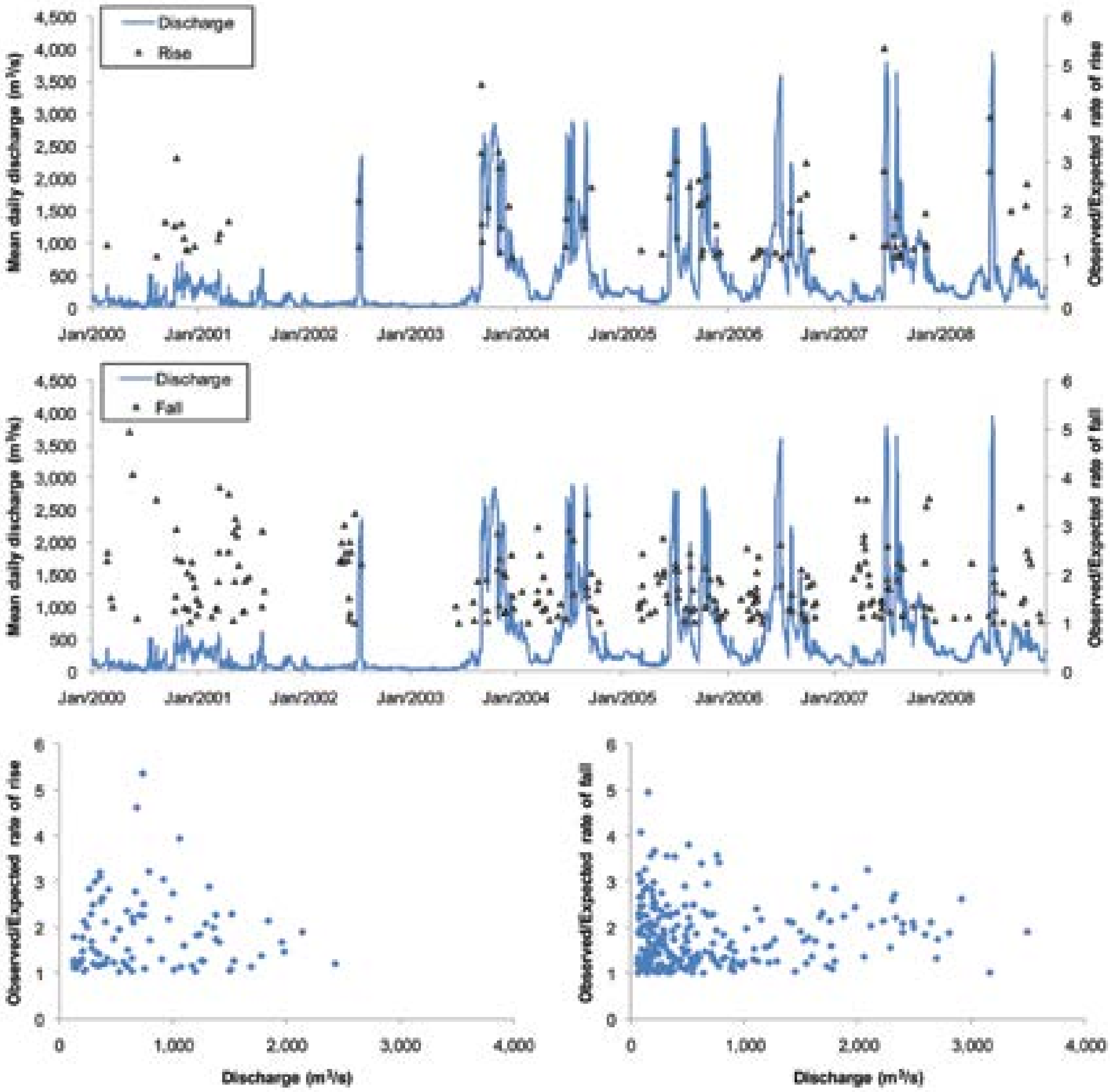
Note: Lower figures plot the same data in scattergraph form.

Figure 61. Mean daily discharge hydrograph at Luokou for the period 2000 to 2006 (post-Xiaolangdi Dam), showing the O/E 90th percentile rates of rise and fall for O/E values exceeding 1.



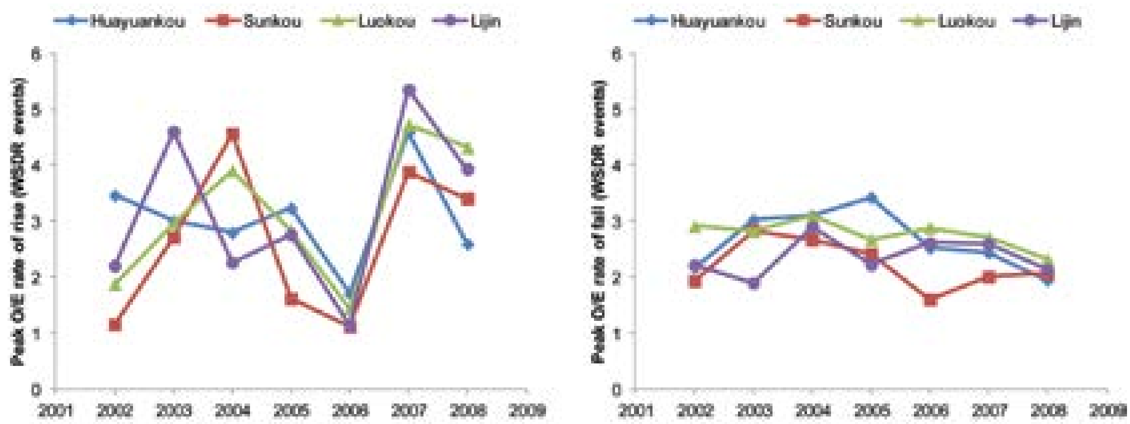
Note: Lower figures plot the same data in scattergraph form.

Figure 62. Mean daily discharge hydrograph at Lijin for the period 2000 to 2006 (post-Xiaolangdi Dam), showing the O/E 90th percentile rates of rise and fall for O/E values exceeding 1.



Note: Lower figures plot the same data in scattergraph form.

Figure 63. Peak values of O/E 90th percentile rates of rise (left) and fall (right) for the annual WSDR events.



Note: The standard for good river health is O/E ≤1.

6.6.10 Flood frequency

Traditional flood frequency analysis (Gordon et al. 2004, pp. 204–211) is usually undertaken for environmental flow assessment, as a way of indicating the degree of change in flood recurrence intervals. Spells analysis is also a form of flood frequency analysis, but it has the advantage of also including information about event timing and duration. For some flood events (particularly the larger events), the timing and duration may not be very important from the ecological and geomorphological perspectives, in which case flood frequency analysis is an adequate method of characterisation.

Flood frequency analysis was undertaken using data from the Huayuankou gauge, for the pre-Sanmenxia (close to natural) and the post-Xiaolangdi (current) phases of regulation. In order to obtain some information about event timing, the data were split into two seasons: high flow (June to November) and low flow (December to May), with a further period defined within the low flow season, called snowmelt (May to April). A partial duration series was derived for each flow series, and polynomial curves were fitted to the distributions (Figure 64). The discharges corresponding to a range of average recurrence intervals (ARI) were estimated using the fitted relationships (Figure 65).

There has clearly been a major decline in the magnitude of events with the same ARI since the operation of Sanmenxia Dam (Figure 65). The largest relative decline is in the high flow season (Figure 65). This reflects the management objective of storing water during the flood season in most of the dams in the basin, and it also highlights the effectiveness of flood prevention measures. It can be seen that in the snowmelt season, the current and natural flood magnitudes are similar for floods that occur more frequently than 2 times per year on average, but there is a noticeable difference for less frequent events (Figure 65). This is because the higher events (higher than approximately 1000m^3/s) were previously sourced from snowmelt, and this snowmelt is now largely captured by dams.

Figure 64. Partial duration series for Huayuankou for three seasons, and two regulation periods.

Note: The period 1949–1960 is pre-Sanmenxia and the period 1999–2008 is post-Xiaolangdi Dam. The modelled curves are polynomial relationships fitted to the data.

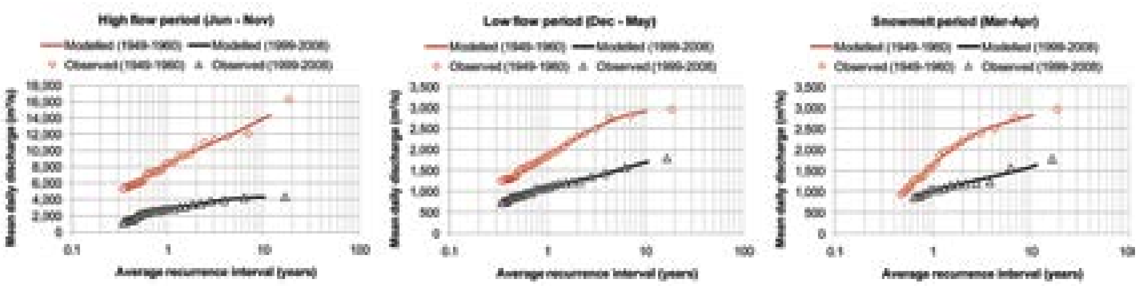
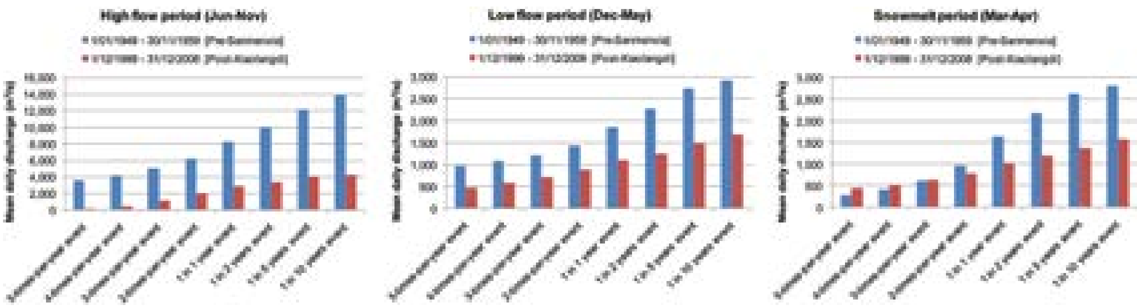


Figure 65. Estimated magnitudes of events over a range of average recurrence interval (ARI) for Huayuankou during three seasons, and two regulation periods.



Chapter 7. Water Quality

7.1 Nutrients

7.1.1 Nitrogen

Nitrogen contamination of river water is recognised as a serious problem globally (Camargo and Alonso 2006) and the Yellow River is no exception (e.g. Xia et al. 2002; Zhang et al. 2007). According to Deltares (2009, p. 27) there has been a 10-fold increase in nitrogen flux of the Yellow River to the sea since the industrial and agricultural revolutions.

Nitrogen naturally occurs in various forms[18], with ammonia being of most concern in aquatic environments. Excess ammonia contributes to eutrophication of water bodies. This results in prolific algal growths that have deleterious impacts on other aquatic life, drinking water supplies, and recreation. The analytical test for ammonia nitrogen measures total ammonia (NH_3 + NH_4^+), although the literature often uses the notation NH_4^+ (ammonium) for total ammonia nitrogen, because ammonium normally makes up the bulk of the total ammonia nitrogen[19]. The other widely measured nitrogen parameter is TN (total dissolved nitrogen)[20].

Four studies have analysed nitrogen data from the lower Yellow River: Xia et al. (2002), Chen et al. (2004), Fan and Huang (2008) and Yu et al. (2010). These studies used some common data sources, so not surprisingly reached similar conclusions. Xia et al. (2002) analysed nitrogen data collected in 1980, 1990, 1997, and 1999 from streams around the basin. They found that increasing nitrogen concentrations in the tributaries in the downstream direction led to an increase in the nitrogen concentration of the mainstream from the upper to the lower reaches. Nitrogen in the river water was attributed mainly to point sources. Also, the NH_4^+-N and TIN content of the river water increased significantly in the mainstream and the tributaries over the 1980–1999 period. At Lijin, the NH_4^+-N mean concentration was 0.04 mg/L in 1980, 0.11 mg/L in 1990, and 0.36 mg/L in 1999. The TIN concentration at Lijin rose from 1.3 mg/L in 1990 to 4.6 mg/L in 1999. The change over time was associated with an increase in wastewater discharge and nitrogenous fertilizer application in the Yellow River catchment (Xia et al. 2002).

Yellow River Basin nitrogen data were also analysed by Chen et al. (2004). The study revealed that in agricultural areas with less developed industries and cities, nitrogen concentration in the flood season months (July to September) was remarkably higher than that in dry season months (December to February). This was explained in terms of excess fertiliser washing into the river. In the areas with dominant industries and municipalities, nitrogen concentration in the flood season was remarkably less than in the dry season. This was explained by the influence of the discharge of municipal sewage and industrial liquid waste being relatively greater in the dry season due to less dilution by smaller river flows. In other areas there was no seasonality to the pattern of nitrogen concentration.

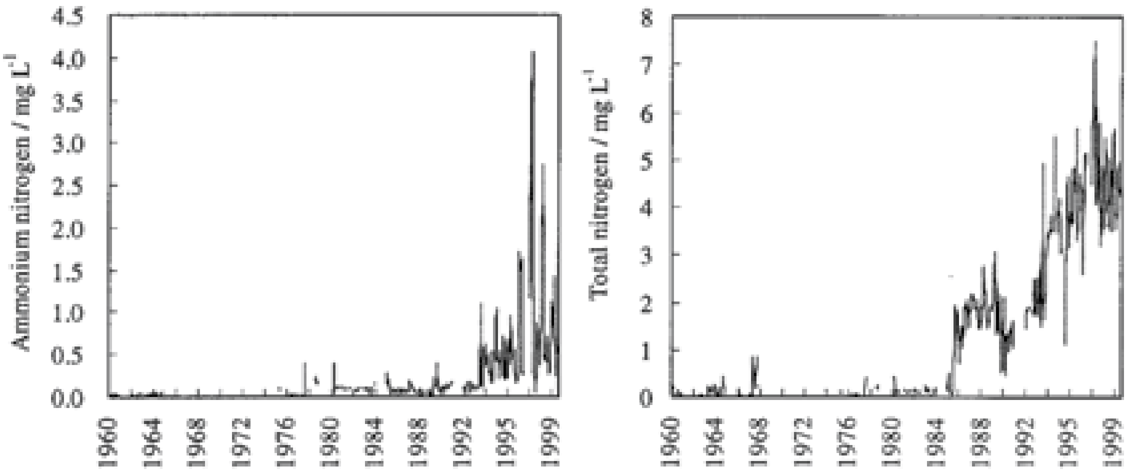
The data of Chen et al. (2004) show how NH_4^+-N and TN concentration in river water at all Yellow River basin sampling stations, including Luokou on the lower river, increased significantly between 1960 and 2000 (Figure 66). The pattern was correlated with a number of socio-economic indicators (the nitrogen fertiliser application rate, density of population, number of livestock, general industrial output and GDP), and it was assumed by Chen et al. (2004) that sewerage and industrial effluent discharges also increased over this period. An abrupt change point for NH_4^+-N concentration occurred at all stations in 1990–1994, when levels began to increase markedly. Nitrogen trends at Luokou were consistent with the increasing duration of cease to flow between 1972 and 1997. In other words there was a strong inverse relationship between river flow and nitrogen concentration (Chen et al. 2004).

18 Nitrogen can come from organic sources (plants and animals) or inorganic, or mineral, sources (precipitation, fertiliser). In the organic form, nitrogen is bound by carbon. Bacteria convert the organic form to the inorganic form, which allows the nitrogen to be available for use by plants. Water quality programs test for inorganic nitrogen.

19 There are two forms of ammonia, un-ionised or free (NH_3) and ionised (NH_4^+). Only the un-ionised form is toxic. Of the total ammonia nitrogen (TAN) present in water, the proportion of the toxic NH_3 form increases with temperature and pH, e.g. at 25°C, in fresh water of pH 7, it makes up less than 0.1% of the total but at pH 8.5 it can make up more than 10% of the total. Therefore, ammonia is less toxic at lower pH levels. The Chinese Environmental Quality Standard for Surface Water (GB 3838-2002) uses the symbol NH_3-N, which we assume refers to the analysis of total ammonia nitrogen.

20 TIN (total inorganic nitrogen) or DIN (dissolved inorganic nitrogen) is the sum of inorganic nitrogen (NH_4^+-N, NO_2^--N (nitrite) and NO_3^--N (nitrate)). TN is the sum of inorganic nitrogen and organic nitrogen. Ammonium (NH_4^+) is the form of nitrogen taken up most readily by phytoplankton because nitrate (NO_3^-) must first be reduced to ammonia before it is assimilated into amino acids in organisms.

Figure 66. Changes in ammonium nitrogen and total nitrogen concentrations at Luokou station, Shandong Province (1960–2000).



Source: Chen et al. (2004).

Fan and Huang (2008) observed that TN concentration at Lijin increased four-fold between 1958 and 1990. This was attributed partly to increased discharge of wastewater and increased fertiliser application, and partly to the reduced discharge of the river (i.e. less dilution of pollutants).

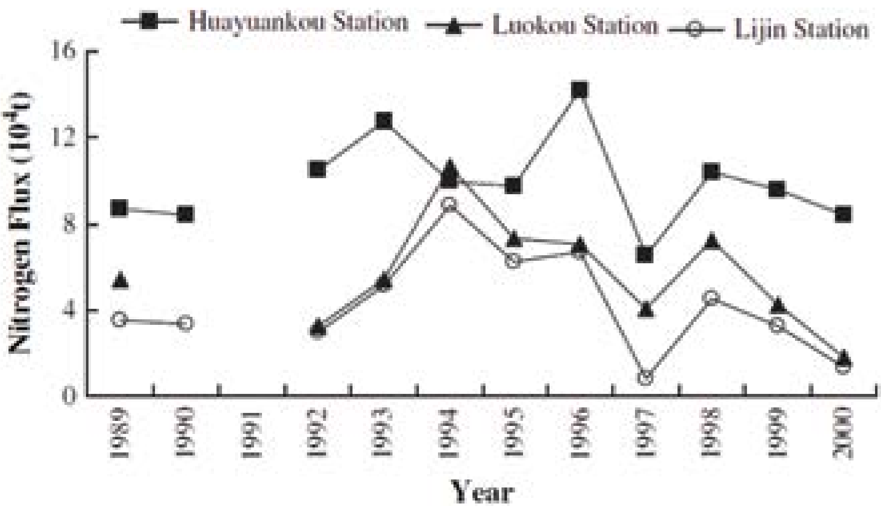
Yu et al. (2010) examined DIN[21] data from Huayuankou, Luokou and Lijin for the period 1960-2000. They also reported data on the same socio-economic indicators reported by Chen et al. (2004) and also found and increasing trend in total nitrogen concentration over the period of observation, with step changes in the early 1980s and early 1990s at Huayuankou Station and a step increase in the early 1990s at Luokou and Lijin Stations. The concentrations through time were similar at the three stations. Yu et al. (2010) also calculated the annual nitrogen fluxes (loads) at the three stations (Figure 67). The data indicated that the load was lowest in the year of lowest flow (1997), and that there was a trend of increasing load before 1997 and a decreasing trend after 1997 (Yu et al. 2010). The pattern of loads was synchronous at the three stations, but the loads were lower the further downstream. This was explained by downstream decline in discharge, due to lack of tributary inflows, and diversions for irrigation, domestic and industrial uses. Nitrogen concentration was positively and significantly correlated with population size and nitrogen fertilizer use in the basin, but was not correlated with industrial discharge, leading Yu et al. (2010) to conclude that population growth and fertiliser use were the main causal factors in the observed trends.

Like Xia et al. (2004) and Xia et al. (2009), Zhang XQ et al. (2007) undertook laboratory experiments using water sampled from the lower Yellow River that demonstrated the presence of high-suspended solids concentration could accelerate the nitrification process[22]. Given the high concentration of suspended solids typical of the lower Yellow River, Zhang XQ et al. (2007) were curious about why the ammonium nitrogen (NH_4^+-N) levels in the lower Yellow River were so high in both the flood season and non-flood season.

21 Yu et al. (2010) used the notation DIN (total dissolved inorganic nitrogen) for total nitrogen. Chen et al (2004) used the notation TN (total organic and inorganic nitrogen) for total nitrogen, but their plots suggest that these two studies used the same data.

22 Nitrification is a natural biological process during which aerobic chemo-autotrophic bacteria convert ammonia to less harmful nitrate.

Figure 67. Nitrogen flux (load) at three lower Yellow river sites from 1989 to 2000.



Source: Yu et al. (2010).

Zhang XQ et al. (2007) explained that the excessive and continuous input of nitrogen contaminants to the river was the fundamental reason for the high concentration of ammonium nitrogen. They found that when present in high concentrations, organic and ammonium nitrogen inhibited the nitrification processes (i.e. regardless of suspended solids concentration). When the initial NH_4^+-N concentrations were 10.1, 18.4 and 28.2 mg/L, nitrification efficiencies were 17.4 per cent, 13.0 per cent and 2.5 per cent, respectively. The oxygen-consuming organics and toxic substances existing in the river water could inhibit the activity of nitrifying bacteria, and thus lead to the accumulation of ammonium nitrogen. Also, a high pH value of river water resulted in a high concentration of toxic non-ionic ammonium nitrogen (NH_3), which would reduce the activity of nitrifying bacteria and decrease the nitrification rates. In the non-flood season, a high level of ammonium nitrogen persisted because of low river runoff (and low dilution), low suspended solids concentration, and low activity of nitrifying bacteria.

7.1.2 Phosphorus

Phosphorus can occur in numerous organic and inorganic forms, and may be present in river water as dissolved and particulate species. Natural sources of phosphorus include the weathering of rocks, in addition to the decomposition of organic matter. There is high natural variation in phosphorus levels associated with characteristics of regional geology (DWAF, 1996). Elevated levels of phosphorus may result from point-source discharges such as domestic and industrial effluents, and from diffuse sources (non-point sources), which is dominantly soil erosion. The most significant effect of elevated phosphorus concentrations is its stimulation of the growth of aquatic plants (DWAF, 1996). Excess phosphorus contributes to eutrophication of water bodies.

Li and Yu (1999) estimated the phosphorus budget of the Yellow River estuary using data collected in 1989. The annual phosphorus load to the estuary was 0.87 × 10^6 tonnes. Of this, 32.3 per cent was solubilised (released from suspended matter and sediments), 67.5 per cent was deposited and buried in marine sediments, and only 0.2 per cent (1600 tonnes) was contributed as dissolved phosphorus from river water.

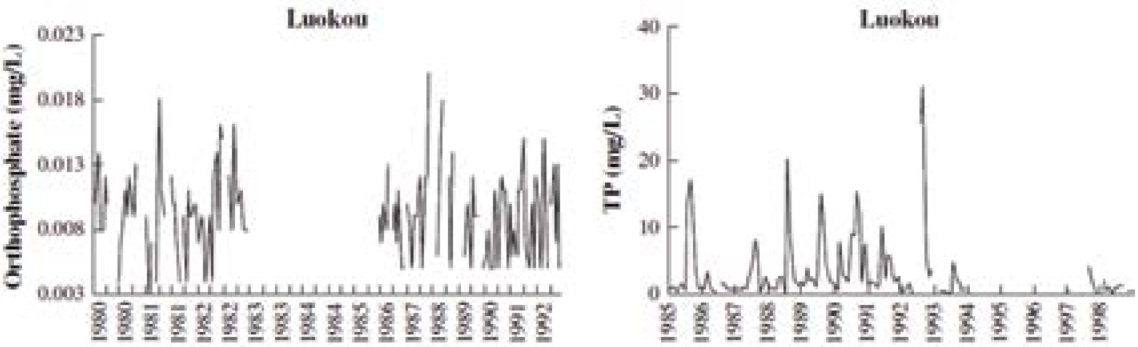
Yu et al. (2010) reported on phosphorus data from the lower Yellow River over the period 1980–1998. Orthophosphate (SRP)[23] was monitored twice a month from 1980 to 1984 and once in a month from 1985–1993; total phosphorus (TP)[24] was monitored once per month from 1985 to 1998. The average SRP concentration from 1980–1992 was 0.009 mg/L (n = 131); the average TP concentration from 1985 to 1998 was 3.095 mg/L (n =134) at Luokou station (Figure 68). Compared with other rivers of the world, these data position the Yellow River as the richest in total phosphorus (Yu et al. 2010). However, as the SRP concentration was less than 1 per cent of the TP concentration (mean SRP/mean TP = 0.3 per cent), the phosphorus in the Yellow River mainly appears in the particulate-bound form, which agrees with the estuary phosphorus budget of Li and Yu (1999).

23 Orthophosphate is the chemically active dissolved form of phosphorus also known as soluble reactive phosphorus (SRP) and is the form that is readily available for uptake by plants and algae. SRP levels fluctuate daily.

24 Total phosphorus (TP) includes SRP and particulate phosphorus associated with suspended matter. TP concentration is more stable through the day than SRP concentration. Non-SRP components of TP can be converted to orthophosphate after decomposition.

Unlike nitrogen data (Figure 66), the phosphorus data showed no consistent trend through time (Figure 68) (Yu et al. 2010). There is a suggestion in the data that TP concentration reduced in association with reduced discharges in the 1990s (Figure 68). This reduction was explained by Yu et al. (2010) in terms of the reduced concentrations of suspended solids (with much of the TP being particulate-bound) associated with lower flows. In contrast, there was no decline in dissolved phosphorus (SRP) in the 1990s. Yu et al. (2010) found that, unlike nitrogen concentration, total phosphorus concentration was not correlated with socio-economic indicators. However TP was very strongly correlated with total suspended solids concentration (TSS) ($r = 0.965$, $P < 0.01$). The derived relationship between TP and TSS was in agreement with the measured phosphorus content of soil from the Loess Plateau. Yu et al. (2010) concluded that because the soil loss component dominates phosphorus load in the lower Yellow River, contributions of phosphorus from other sources such as agriculture or detergents, which may be significant, are masked by the abundance of soil-related phosphorus.

Figure 68. Patterns of orthophosphate (SRP) and total phosphorus (TP) at Luokou from 1980 to 1998. Source: Yu et al. (2010).



7.2 Oxygen-consuming organics

The presence of dissolved oxygen (DO) is essential to maintaining life in the aquatic environment. The DO level in water is constantly changing and represents a balance between respiration and decomposition that deplete oxygen and photosynthetic activity that increases it. The solubility of DO is directly proportional to the partial pressure in the gas phase, and to salinity and temperature. Thus, while DO is a direct measure of oxygen availability, its concentration is naturally variable through the day. Organic waste may cause depletion of the oxygen supply in the water. The same result can be achieved in waters rich in nutrients that cause algal blooms whose eventual decomposition uses up the available dissolved oxygen. On the other hand, the concentrations of oxygen consuming organics (OCOs), BOD_5, COD, and Chemical Oxygen Demand Permanganate Index (COD_{Mn}), are more stable than DO, and because they are good indicators of the potential for oxygen depletion, they could be considered preferable indicators of the oxygen balance in streams. Concentrations of nutrients are also potential indicators of oxygen depletion when levels are high enough to promote algal blooms.

BOD_5 refers to the amount of oxygen consumed when the organic matter in a given volume of water is biodegraded in an incubation test. COD refers to the amount of oxygen consumed when the organic matter and other reducing matter in a given volume of water is chemically oxidised by a strong chemical oxidant, such as potassium permanganate (COD_{Mn}) or potassium dichromate (COD_{Cr}). In China COD measured using dichromate is referred to simply as COD (Chen et al. 2006). The effectiveness of potassium permanganate in oxidising organic compounds varies widely and it may not be able to effectively oxidize all organic compounds in water, whereas potassium dichromate (which is used in combination with boiling sulfuric acid) is not specific to oxygen-consuming chemicals that are organic or inorganic (Chen et al. 2006). Despite the variable oxidation effectiveness of permanganate, in China, COD_{Mn} was traditionally considered to be the most important parameter to reflect the degree of pollution by OCOs in surface waters (Xia et al. 2005), although since 1998 COD was added to routine monitoring programs (Chen et al. 2006).

Xia et al. (2005) analysed OCO data collected from sites within the Yellow River Basin in 1980 and in the period 1992–1999. The annual average concentration of BOD_5 increased from 1980–1992 from 1.1 mg/L to 3.6 mg/L at Huayuankou and 0.7 mg/L to 2.2 mg/L at Lijin. The average concentration of BOD_5 in the non-flood season increased significantly during this period while the increasing trend was not significant in the flood season. The increasing rate of BOD_5 concentration during 1992–1999 was much lower than from 1980–1992. Consistent with increasing trend of BOD_5 concentration in the mainstream during the period 1992–1999, annual average concentrations of DO in river water in 1999 were much lower than those in 1992.

Xia et al. (2005) noted that significant differences were apparent between the temporal and spatial characteristics of COD_{Mn} and BOD_5 concentrations in river water. First, the average BOD_5 concentration in the non-flood season was higher than in the flood season, whereas COD_{Mn} showed the reverse pattern. Second, during the period 1992–1999, annual average concentration of BOD_5 showed an increasing trend in most Yellow River basin hydrological stations, while COD_{Mn} showed a decreasing trend at most hydrological stations. Finally, the total load of BOD_5 showed an increasing trend during the period 1992–1999, while COD_{Mn} showed a decreasing trend (Xia et al. 2005). To explain these differences, Xia et al. (2005) proposed that the natural humic substances associated with the high suspended solids concentrations of Yellow River water samples were consumed by chemical oxidants and therefore contributed to COD_{Mn} values, but were not much oxidised in the biological incubation test, so did not contribute to BOD_5. Xia et al. (2005) concluded that because the COD_{Mn} value exaggerated the degree of OCO pollution it was not a suitable index of oxygen balance of the river.

Annual wastewater discharge in the Yellow River basin increased from 2.17 × 10^9 tonne in 1980 to 3.26 × 10^9 tonne in 1990 and then to 4.00 × 10^9 tonne in 1997. Xia et al. (2005) concluded that the observed increase of BOD_5 in river water during the period 1980–1997 was related to the increase of wastewater discharge. This led to the increasing trend of BOD_5 in the non-flood season. In contrast, the load from non-point sources showed a decreasing trend during the period 1992–1998, which was caused by the decreasing trend of suspended solids load. Overall, the total load of OCOs, as reliably measured by BOD_5, manifested an increasing trend in the period 1992–1998.

BOD_5 and COD data from the Yellow River for the period 1989–2002 were analysed by Chen et al. (2006). Citing Chapman (1992), Chen et al. (2006) noted that the concentrations of COD normally observed in surface waters range from 20 mg/L or less in unpolluted waters to 200 mg/L in waters receiving effluents. However, in parts of the Yellow River, COD levels 10 or even 100s of times higher than this have been recorded, and this was from sites *not* directly below effluent discharge points. In contrast, other highly polluted urban rivers in China do not show such extreme COD values. To add to the confusion, the OCO parameters are surprisingly not necessarily correlated. Chen et al. (2006) undertook some laboratory experiments that confirmed the hypothesis of Xia et al. (2005) (see above) that COD values of unfiltered Yellow River water can have little to do with the content of degradable oxygen-demanding organic matter discharged into the river from sewage but can rather reflect, to a larger degree, the content of natural organic matter in the sediment. This depends on location; in some polluted areas the COD reflects high concentrations of oxygen consuming organics, while in less polluted sections, especially in the flood season, natural organic matter makes up the major proportion of COD. Chen et al. (2006) also found that even if the sample was filtered prior to analysis, the COD value could still be inflated because some fraction of natural organic matter in the sediment is soluble in water. Chen et al. (2006) concluded that compared with COD, BOD_5 can better describe water pollution in the Yellow River. However, as the BOD_5 test is performed on unstirred samples, Chen et al. (2006) believed that reported BOD_5 values underestimated actual BOD.

Together, the studies of Xia et al. (2005) and Chen et al. (2006) present a compelling case to disregard the raw COD and COD_{Mn} data from the Yellow River as suitable indicators of organic pollution. DO and BOD_5 appear to be better oxygen balance parameters.

7.3 Elemental ions (dissolved solids)

Natural chemical water quality is usually expressed by eight dominant ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-}), which usually account for 98–99 per cent of total dissolved solids (TDS) in natural water (Chen and He, 2003). The TDS of Yellow River water is among the highest in China and also the world (Chen and He, 2003; Zhang et al. 1995). This is attributable to the abundant carbonates in the loess in the central part of the basin together with the arid and semi-arid climate of the basin (Zhang et al. 1995). While the high dissolved load is associated with weathering and erosion of loess, Zhang et al. (1995) pointed out that the modern erosion rates are accelerated above expected natural rates due to agricultural practices.

Analysis of elemental ion chemistry data collected over the period 1960-2000 by Chen and He (2003) revealed a statistically significant upward trend for all mainstream stations downstream of the main irrigation areas beginning at Qingtongxia (in the middle Yellow River). Chen and He (2003) concluded that the increasing trend was mainly a result of saline irrigation return waters, plus a contribution from evaporation in reservoirs.

7.4 Dissolved metals and metalloids

A study of the dissolved metals Cd, Cr, Cu, Ni, Pb and Zn was recently undertaken by Feng et al (2010) for waters and sediments at 23 sites on the lower Yellow River and tributaries in the Henan reach. Generally, metal concentrations were found to decrease in sequences of Zn > Cu > Pb > Cr > Ni > Cd in water and Zn > Cr > Pb > Ni > Cu > Cd in sediments. High levels of metal concentration in water were determined at a few stations of the river and its tributaries, such as Yiluo, Si and Qin rivers.

The pollution of waters of the Yellow River by Cd, Cr, Cu, Ni, Pb and Zn can be regarded as much higher compared to the background values, US EPA criteria (1999) and China water quality criteria (2002) (Feng et al. 2010). For sediments, metal levels except Pb did not significantly exceed the average shale levels and backgrounds in several countries including China. Feng et al. (2010) suggested that wastewaters discharged by industry (e.g. mine plants, smelter plants, power plants, battery plants, tannery plants) and sewage inputs from the cities along the river banks were likely sources of metals to the river water.

Arsenic is a highly toxic metalloid, introduced into water through the dissolution of minerals and ores, and also through some industrial effluents. Zhang et al. (1993) found that in a survey of the Yellow River from the headwaters to the sea, arsenic concentrations at most stations exceeded the surface water quality standards. In particular, arsenic concentrations increased markedly in the middle reach of the river through the Loess Plateau. The highest concentration (0.161 mg/L) occurred at Huayuankou. Zhang et al. (1993) also found that arsenic in some fish samples exceeded health standards for consumption. Through the Loess Plateau, the contribution of sediment with high arsenic content caused river water concentrations to greatly exceed the water quality standard (Zhang et al. 1993). Arsenic concentrations increased markedly again downstream at Hauyuankou. That increase was attributed to re-suspension of high arsenic sediment that was previously deposited in the Sanmenxia Reservoir (Zhang et al. 1993). High concentrations of arsenic found in water and particulate matter in the Yellow River by Huang et al. (1998) were also attributed to the high arsenic content of the loess deposits.

7.5 Phthalic acid esters

Phthalic acid esters (PAEs) are often used as plasticisers, pesticide carriers, and materials of parasiticides, cosmetics, fragrances and lubricants. PAEs may be harmful to humans and also to aquatic organisms, especially with respect to reproduction (Meyer and Sanders 1973). Sha et al. (2007) collected samples of water, sediment and suspended particulates from 13 sites in the lower reaches of the Yellow River from the Xiaolangdi Dam to the Dongming Bridge (317 km downstream) in June 2004. Seven sites were located on the mainstem and 6 on tributaries. In the mainstem, PAEs concentrations in water phase ranged from 3.99×10^{-3} to 45.45×10^{-3} mg/L, and that of the tributaries ranged from 15.80×10^{-3} to 49.53×10^{-3} mg/L. These concentrations were generally comparable to the levels of PAEs found in water in other rivers in the world. However, the concentrations of Di (2-Ethylhexyl) Phthalate (DEHP) in the water phase exceeded the quality standard at all stations except those at Mengjin and Jiaogong Bridge of the main river. The concentrations of PAEs in the sediment phase of the main river were 30.52 to 85.16 mg/kg, which were much higher than those of other rivers in both China and other countries. The range of PAE concentrations in suspended particulates was from 40.56 to 94.22 mg/kg.

7.6 Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) can be introduced to the aquatic environment through wastewater discharge, atmospheric deposition, surface runoff, and oil leaks (Sun et al. 2009). Fossil fuel combustion is a source of PAHs in the environment. Due to their carcinogenicity, mutagenicity and toxicity, 16 PAHs are included in the list of priority pollutants of the US EPA. Once PAHs enter water they tend to be associated with particulate matter and subsequently deposit in sediments.

Sun et al. (2009) sampled water, suspended sediment and bed sediments from sites in the Henan reach of the Yellow River (from Tongguan to Dongping Hu, including tributaries), in November 2005 and August 2006. Observed levels of 16 PAHs ranged from 144 to 2,361 ng/L (ng = 10^9g) in water, from 507 to 10,510 ng/g in suspended particulate matter and from 16.4 to 1,358 ng/g in sediment. The results suggested that sediments from the Henan reach of the lower Yellow River were mainly contaminated by pyrolytic PAHs. This could be explained by coal burning being the main source of energy in this area. In some sites the sources could also be petrogenic (petroleum industry and chemical plants). A risk assessment was undertaken using reference standards from The Netherlands (as there were no local standards). The assessment concluded that the ecosystem risk presented by PAHs in the aquatic environment of the Henan reach of the Yellow River was generally relatively low. However, some toxicity might be caused by certain PAH components (Sun et al. 2009).

A study of the distribution of 16 PAHs in the water column of Yellow River delta by Wang X et al. (2009) found concentrations to be at relatively low or medium levels (average of 121.3 ng/L in water and 209.1 ng/g in suspended particulate matter). Comparing these data with those of Sun et al. (2009) (see above), it is apparent that PAHs levels are lower in waters of the delta compared to those in the Henan reach of the Yellow River. The probability risk assessment, like that of Sun et al. (2009), concluded that the risk associated with PAHs in waters of the delta was low. The investigation found that the sources of PAHs in the delta waters were both pyrogenic and petrogenic.

7.7 Organochlorine pesticides

Persistent organic pollutants, especially organochlorine pesticides (OCPs), represent a global contamination problem because of their large production and usage, ubiquity, high bioaccumulation potential, persistence in the environment, and high toxicity to non-target organisms (Jones and de Voogt, 1999). China is the second largest country producing and using OCPs in the world (Wang G et al. 2010).

Wang, G et al. (2010) sampled sediment from 26 mainstem and tributary sites in the middle and lower Yellow River and analysed them for selected organochlorine pesticides. Concentration of OCPs in the sediments from the Yellow River ranged from 0.05 to 5.03 ng/g (mean, 1.02 ng/g) for ∑DDT (dichlorodiphenyltrichloroethane), and 0.09 to 12.89 ng/g (mean, 1.08 ng/g) for ∑HCH (gamma-hexachlorocyclohexane). The concentration distribution of ∑DDT and ∑HCH varied significantly among sampling stations, indicating their different contamination sources. The Yiluo, Xinmang, and Jindi rivers, three of the main branches of the Yellow River in middle and lower reaches, were seriously contaminated by DDT and HCH (Wang G et al. 2010). Composition analyses demonstrated that residues of DDTs in sediments came from the previous extensive use of organochlorine pesticides in the middle and lower catchment areas (especially Lindane) (Wang G et al. 2010).

Tai et al. (2008) showed that HCHs and DDTs were the dominating components of OCPs in both water and sediment sampled in 2007 from the Mengjin Huanghe Nature Reserve. The HCHs were the dominating components in water, whereas the DDTs were the dominating components in sediment. In the water sampled from Mengjin wetland, the OCPs content in the medium flow period (5.11 to 12.21 ng/L) was higher than that in the low flow period (up to 4.83 ng/L) and high flow period (up to 5.77 ng/L). Similar trends were established for sediment sampled from Mengjin wetland, for which OCPs content in the medium flow period (up to 64.58 ng/g) was higher than that in the low flow period (up to 40.43 ng/g) and high flow period (7.21 to 24.17 ng/g). Tai et al. (2008) did not compare the measured levels of OCPs with any standards, or assess the risk to the ecosystem. However, the levels recorded in Mengjin sediments were notably higher than those measured in sediments from the Yellow River by Wang G et al. (2010).

7.8 Acid pharmaceuticals

Wang L et al. (2010) investigated the occurrence of twelve acidic pharmaceuticals (salicylic acid, clofibric acid, ibuprofen, gemfibrozil, fenoprofen, naproxen, ketoprofen, mefenamic acid, tolfenamic acid, diclofenac, meclofenamic acid and indomethacin) in surface waters of the middle and lower Yellow River (also the Hai River and Liao River) during the flood and non-flood seasons.

Among the 12 acidic pharmaceuticals analysed in surface waters from the Yellow River in both seasons, five non-steroidal anti-inflammatory drugs (NSAIDs) (salicylic acid, ibuprofen, naproxen, mefenamic acid and diclofenac), and two blood lipid regulators (BLRs) (clofibric acid and gemfibrozil) were detected in the water samples (Wang L et al. 2010). Salicylic acid, ibuprofen and diclofenac were detected at nearly all sampled sites, with concentrations up to 121, 416 and 136 ng/L respectively. The other two NSAIDs were found with lower concentrations. Clofibric acid and gemfibrozil were found at maximum concentrations of 6.4 ng/L and 13.5 ng/L, respectively (Wang et al. 2010).

The concentrations for acidic pharmaceuticals in the Yellow River were in most cases higher in the dry season than in the wet season. High concentrations of these compounds were found more frequently at sites located near highly urbanised areas, lower reaches or river confluences. Comparing the maximum measured concentrations against standards for no effect on aquatic organisms, only diclofenac and ibuprofen were found to have medium to high risks to the aquatic organisms. As the highest concentrations of pharmaceuticals were found near highly urbanised areas, Wang L et al. (2010) suggested that risk reduction could be achieved through application of proper sewage treatment technologies.

7.9 Estuary water quality issues

The salinity of the Bohai near the estuary is very sensitive to the discharge of freshwater from the Yellow River. There was a significant rise in the salinity near the estuary in the 1990s in response to declining river discharge (Fan and Huang 2008).

The load of dissolved inorganic nitrogen to the estuary in 1997 (the driest year on record) was one-tenth of that in 1984. Fan and Huang (2008) inferred that decreases of river nutrient loads impaired phytoplankton growth in the estuary, which in turn depressed the prawn fishery. Fan and Huang (2008) also presented information from previous research that demonstrated that the number of species, density of fish communities and biomass decreased in response to reduced discharge in the Yellow River, beginning in the 1980s.

In June 2001, Liu et al. (2004) sampled the river mouths around Bohai, including the Yellow River, and tested for nutrients and metals. All of the river mouths were seriously polluted, with the main pollutants being phosphorus, nitrogen and mercury (Hg). Eight of the 12 sampled sites exceeded Grade V of the China standard for surface water quality. The Hg content in the Yellow River mouth was 0.0005 mg/L, and has remained nearly unchanged compared with that of the 1980s, but the waters at Dongying Harbour and Gudong Groyne had Hg concentrations exceeding 0.0015 mg/L (the upper limit for Grade IV is 0.001 mg/L). This result suggested that wastewater directly discharged by the oil and petrochemicals industries in the Yellow River Delta was likely to be responsible for local pollution, rather than Hg pollution near the river mouth being caused by the Yellow River itself. TP was low (0.02 mg/L) at the Yellow River mouth, but TN was very high (5.5 mg/L), well exceeding Grade V standard. Liu et al. (2004) attributed this to pollution from domestic sewerage in the catchment, and also local industrial sources. Copper, lead, zinc and arsenic levels were low in the water sample from the Yellow River mouth.

7.10 Major pollution incidents

Giordano et al. (2004) referred to the occurrence of the 'black wave' in 1999:

> '*In the beginning of 1999, a massive discharge of pollutants entered the main channel below Tongguan, causing the water to turn blackish-gray and produce bubbles and foam as high as several meters. Measured COD (Chemical Oxygen Demand) levels were as high as 64.7 mg/L in the main course and 125 mg/L at the entrance of tributary Weihe which are well above 25 mg/L required to be classed as Class 'V — worse.' The black wave, which continued for 20 days and resulted in the shut-off of many river intakes in areas further downstream*'

Xie et al. (2009) noted that there were 40 major pollution incidents on the Yellow River from 1993–2004, including a spill of diesel oil in January 2006.

7.11 Analysis of historical water quality data

7.11.1 Chinese water quality grades and parameters

In China, the state of river and lake water quality is assessed according to the national standard *GB 3838-2002 Environmental Quality Standards for Surface Water*. The standard defines five grades that are suitable for certain uses, and a sixth grade that is not suitable for any purpose (Table 21). The grading of a river's water quality is done through assessment of monthly measurements of up to 24 standard parameters. Each parameter has five ranges of values that correspond to water use Grades I–V, with any value exceeding the limits of Grade V being assigned Grade VI. Thus, a sample of water is analysed for up to 24 parameters, with each parameter value falling within one of six grades; then the sample is assigned an overall grade according to the worst grade of the analysed parameters. A length of river can then be assessed in terms of the per cent of its length that falls within each grade (each sampling point is assumed to represent a certain length of river). This is a straightforward calculation for a single sampling occasion (i.e. a particular historical month), but often, including in Ministry of Environmental Protection Environmental Yearbooks and State of Environment Reports (http://english.mep.gov.cn/standards_reports/), the water quality of rivers in China is reported for a particular year (e.g. Fuggle 2002; Pietz and Giordano 2009, p.112; Giordano et al. 2004, p. 29). The English language literature does not describe how this calculation is undertaken, but presumably it is the worst score of any parameter over all of the samples tested in a year.

Table 21. Chinese water quality grades, according to standard GB 3838-2002.

Grade of water use	Description of water use
I	National nature conservation reserves; water source protection zones
II	Drinking water 1st Class; natural habitat for sensitive and rare aquatic species; fish and crustacean spawning; fish rearing
III	Drinking water 2nd Class (treatment required); sanctuaries for common aquatic species; fish survival in winter; fish migration; aquaculture; contact recreation
IV	Industrial use; active non-contact recreation
V	Industrial cooling only; agricultural irrigation; ordinary (low conservation value) landscape irrigation; passive recreation
VI	Not suitable for any purpose

There is no official separate Chinese water quality standard that applies exclusively to protection of aquatic ecosystems. Separating the use categories of the standard water quality grades, it is apparent that for a minimum level of aquatic ecosystem protection the water quality must be at least Grade III, and during spawning periods Grade II, while a high level of protection requires Grade I (Table 22).

Table 22. Chinese water quality grades, arranged by classes of use, and an arbitrary aquatic health rating. S means suitable for use, and U means unsuitable for use.

	Drinking water			Recreation			Industry agriculture and parks					Ecological river health							
Chinese grade	**Source areas**	**1st class**	**2nd class (requires treatment)**	**Primary contact**	**Secondary contact**	**Passive non-contact**	**Aquaculture**	**General industrial uses**	**Industrial cooling**	**Agricultural irrigation**	**Irrigation of parks and created landscapes**	**National conservation areas**	**Sensitive and rare aquatic species**	**Common aquatic species**	**Fish spawning**	**Fish rearing**	**Fish migration**	**Frish winter survival**	**Arbitrary aquatic health rating**
I	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	High-very high
II	U	S	S	S	S	S	S	S	S	S	S	U	S	S	S	S	S	S	Mod.-High
III	U	U	S	S	S	S	S	S	S	S	S	U	U	S	U	U	S	S	Low-Mod.
IV	U	U	U	U	S	S	U	S	S	S	S	U	U	U	U	U	U	U	Very low
V	U	U	U	U	U	S	U	U	S	S	S	U	U	U	U	U	U	U	Very low
VI	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	No value

Note: S means suitable for use, and U means unsuitable for use.

GB 3838-2002 lists 24 parameters for testing under the standard. These parameters can be grouped into three main categories: physical, chemical and biological. The chemical category can be further grouped into five sub-categories, to give a total of seven categories of parameters (Table 23). In a paper about the Yellow River specifically, Liu and Liu (2009) suggested '…*COD and NH_4 are taken as the most important parameters for evaluating water pollution*…', but also noted that '*GB 3838-2002 can be used to evaluate river health.*

Table 23. The 24 water quality parameters listed in GB3838-2002, arranged by 3 major categories and 5 sub-categories for chemical parameters.

Parameter category	Symbol	Parameter
Physical parameters 物理性指标		
Basic parameter 普通化学指标	°C	Water temperature
Chemical parameters 化学性指标		
Basic parameter 普通化学指标	pH	Relative acidity
Metallic toxicants 有毒金属	Cu	Copper
	Zn	Zinc
	Se	Selenium
	As	Arsenic
	Hg	Mercury
	Cd	Cadmium
	Cr^{6+}	Hexavalent chromium
	Pb	Lead
Non-metallic toxicants 非金属毒物	F-	Fluoride
	CN-	Cyanide
	P*	Volatile phenols
	LAS	Anionic surfactant
	H_2S (DS)	Sulphide
	CH_4	Petroleum hydrocarbons
Nutrients 植物营养元素	TN	Total Nitrogen
	TP	Total phosphorus
	NH_3-N	Ammonia Nitrogen
Oxygen balance parameters 有机物及氧平衡	DO	Dissolved oxygen
	COD	Chemical oxygen demand
	COD_{Mn}	Permanganate Index
	BOD_5	5-day biochemical oxygen demand
Bacterial parameters 生物性指标		
Basic parameter 普通化学指标	Faecal coliform	Faecal coliform

7.11.2 Data availability

The lower Yellow River was divided into four reaches for the purpose of the environmental flow assessment (Table 17). The water quality of each reach was characterised on the basis of monthly data over the period 1994–2009 from a monitoring station located within the reach (Table 24). The data was provided by YRCC. The records had occasional gaps in monthly data for various parameters, but there were sufficient data for each year to calculate an annual value of water quality grade.

Table 24. Lower Yellow River historical monthly water quality data available to this project.

Reach	Gauge	Period of data record	
		Start	End
1. Xiaolangdi to Gaocun	Huayuankou	Jan–1994	Dec–2009
2. Gaocun to Taochengpu	Gaocun	Jan–1994	Dec–2009
3. Taochengpu to estuary	Luokou	Jan–1994	Dec–2009
4. Estuary	Lijin	Jan–1994	Dec–2009

Not all 24 parameters listed on GB 3838-2002 are measured at lower Yellow River stations (Figure 69). For example: Anionic surfactant and Selenium have never been included, Sulphide has only been measured on a few occasions; TN was only monitored in 2002, 2003 and 2004 at Gaocun, Luokou and Lijin, and in 1994-1998 at Huayuankou; around the time of introduction of the new standard in 2002, TP and faecal coliform were included in the monitoring program at Gaocun, Luokou and Lijin; in contrast, at Huayuankou, TP was monitored prior to introduction of the new standard but not afterwards, and faecal coliform has never been monitored; the other main change that happened around the time of introduction of the new standard was that fewer parameters were measured consistently at Loukou station (Figure 69).

7.11.3 Review of standards

From 1 June 2002 water quality data were collected and analysed according to standard GB 3838-2002 *Environmental Quality Standards For Surface Water* (MEP, 2002). This standard replaced GB 3838-88 and GHZB 1-1999. Comparing these standards, the analytical methods are similar, they have the same five grades plus Grade V+, and the concentration limits for each parameter for each grade are the same in most cases (Note: there are some small, and some important, differences). GB 3838-88 included 30 parameters and GB 3838-2002 has 24. GB 3838-88 listed a standard for faecal coliform only for Grade III.

The main differences between GB 3838-88 and GB 3838-2002 are for nitrogen. GB 3838-88 listed nitrate (NO_3^--N), nitrite (NO_2^--N), non-ionic nitrogen (NH_3) and Kjeldahl nitrogen [TKN or total organic and inorganic nitrogen (TN minus nitrate and nitrite)]. GB 3838-2002 lists ammonia nitrogen (NH_3-N) and total nitrogen (TN). Of these, the most important differences relate to ammonia nitrogen (NH_3-N) (Table 25). The ammonia nitrogen standard appears to have been greatly relaxed in the revision of the standards for GB 3838-2002. It is worthwhile comparing these standards with standards adopted in other parts of the world for protection of aquatic life. The target limit for NH_3 in South Africa is 0.07 mg/L, and the chronic effect value is 0.15 mg/L (DWAF, 1996). In Canada, the limit for NH_3 is 0.019 mg/L (CCME, 2010). As the toxicity of ammonia is temperature and pH dependent, the Canadian standards for total ammonia are specific to these conditions, but the standard for each value of temperature and pH is based on the upper limit of 0.019 mg/L of NH_3 (Table 26). In the Australian standard (ANZECC and ARMCANZ, 2000, p. 3.4-5), the trigger values for protecting 99 per cent, 95 per cent, 90 per cent and 80 per cent of species are 0.32, 0.90, 1.43 and 2.3 mg/L total ammonia as NH_3-N at pH 8.0 (standards can also be derived for other pH values).

A limit of 0.02 mg/L for NH_3 for long-term exposure is widely referred to in the literature. In a review of ecological effects of nitrogen pollution in aquatic ecosystems Camargo and Alonso (2006) noted that '*On the basis of acute and chronic toxicity data, water quality criteria, ranging 0.05 – 0.35 mg NH_3–N/L for short-term exposures and 0.01 – 0.02 mg NH_3–N/L for long-term exposures, have been estimated and recommended to protect sensitive aquatic animals.*' Thus the apparently high limits expressed in some standards for NH_3 can be explained in terms of notation used. When the Australian standards refer to limits for 'TOTAL ammonia as NH_3-N' (ANZECC and ARMCANZ, 2000, p. 3.4-10) and the Canadian standards refer to 'total ammonia for the protection of aquatic life (mg L^{-1} NH_3)' (CCMA, 2010, Table 2) and the Chinese standard GB 3838-2002 refers to 'Ammonia-nitrogen (NH_3-N)' they are referring to total ammonia (NH_3 plus NH_4^+), which is the ammonia analytically measured in water samples (Camargo and Alonso, 2006), and not the concentration of NH_3, or free, un-ionised ammonia, the limit of which for protection of aquatic ecosystems is 0.02 mg/L. Thus, in GB 3838-88, NH_3 limits refer to un-ionised ammonia, and the limits for Grades I to IV are consistent with the global standard of 0.02 mg/L. In GB 3838-2002, NH_3-N limits refer to total ammonia nitrogen. The temperature and pH conditions for NH_3-N limits in GB 3838-2002 are not noted, but because the limits are comparable to those of the Australian standard, a pH of 8 can be assumed.

Figure 69. Availability of monthly water quality data for lower Yellow River stations from 1994–2009 for parameters listed on GB 3838-2002.

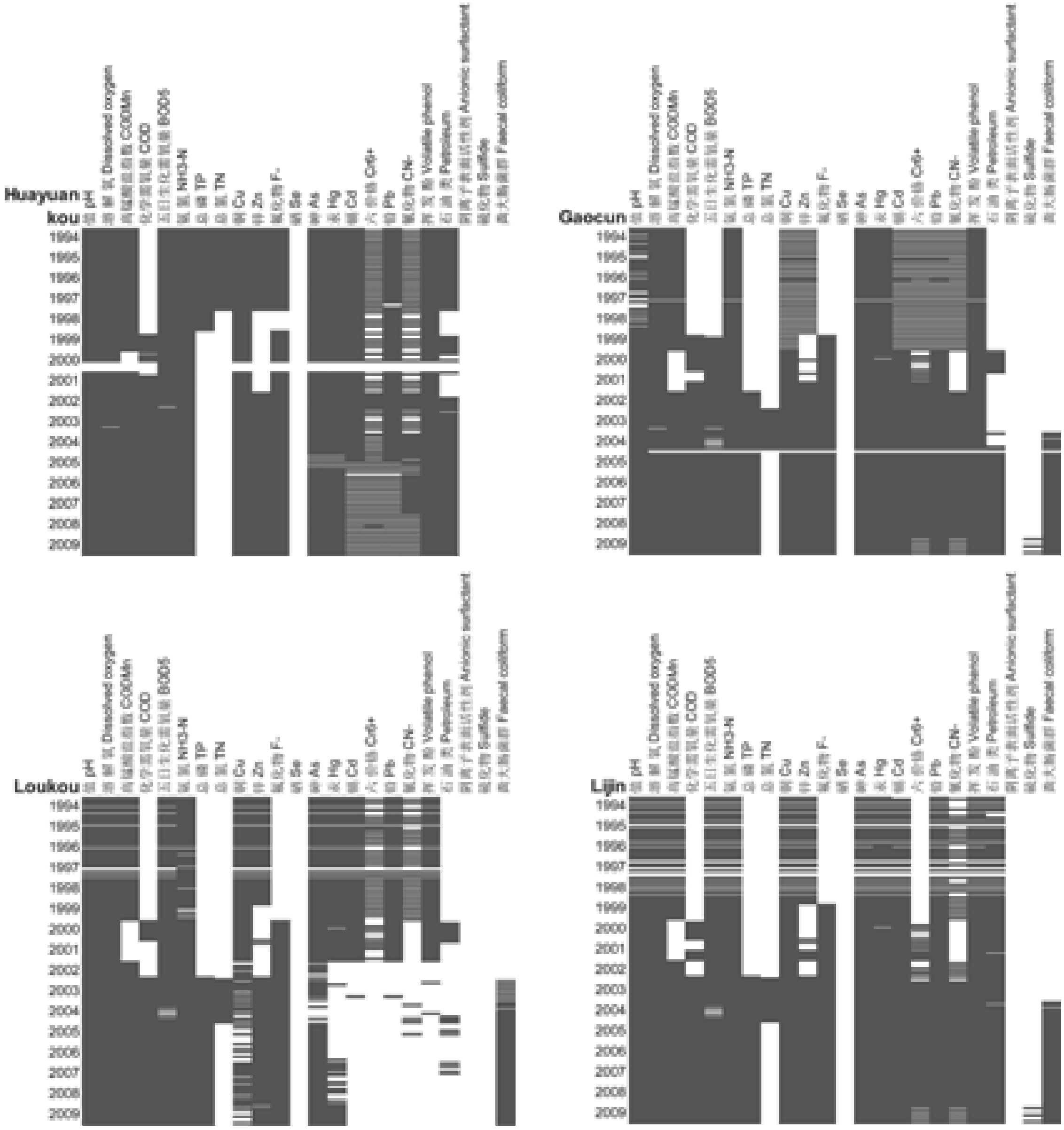


Table 25. Comparison of nitrogen standards in Chinese standards GB 3838-88 and GB 3838-2002.

Parameter	Grade I	Grade II	Grade III	Grade IV	Grade V
GB 3838-88					
Ammonia nitrogen (NH_3)	0.02	0.02	0.02	0.2	0.2
Kjeldahl Nitrogen (TKN)	0.5	0.5	1.0	2.0	2.0
GB 3838-2002					
Ammonia nitrogen (NH_3-N)	0.15	0.5	1.0	1.5	2.0
Total nitrogen (TN)	0.2	0.5	1.0	1.5	2.0

Table 26. Canadian water quality guidelines for total ammonia for the protection of aquatic life (mg/L).

Temp. (°C)	pH							
	6.0	6.5	7.0	7.5	8.0	8.5	9.0	10
0	231	73.0	23.1	7.32	2.33	0.749	0.250	0.042
5	153	48.3	15.3	4.84	1.54	0.502	0.172	0.034
10	102	32.4	10.3	3.26	1.04	0.343	0.121	0.029
15	69.7	22.0	6.98	2.22	0.715	0.239	0.089	0.026
20	48.0	15.2	4.82	1.54	0.499	0.171	0.067	0.024
25	33.5	10.6	3.37	1.08	0.354	0.125	0.053	0.022
30	23.7	7.50	2.39	0.767	0.256	0.094	0.043	0.021

Source CCME (2010).

Total nitrogen can be expressed in a number of ways: as TN (Total Nitrogen) (the sum of organic nitrogen, NH_3 (ammonia), NH_4^+ (ammonium), NO_2^--N (nitrite) and NO_3^--N (nitrate)), TKN (Total Kjeldahl Nitrogen), which is TN minus nitrate and nitrite, TIN (or DIN) (Dissolved Inorganic Nitrogen) which is TN minus organic nitrogen. The Australian standard (ANZECC and ARMCANZ, 2000, p. 3.3-10) and GB 3838-2002 use TN. The Canadian standard (CCM, 2007) uses DIN. The Australian TN standard for reference streams ranges from 0.2 to 1.2 depending on location, and the Chinese standards fall within this range for Grades I to III (Table 25). For Canada the recommended limit, derived from reference site data is only 0.02 mg/L. In the US, for protection of aquatic life the recommended criterion for TN over the 13 eco-regions ranges from 0.12 to 2.18 mg/L (US EPA, 2009). Camargo and Alonso (2006) noted that several studies indicated that total nitrogen (TN) may be related more strongly with algal biomass and toxin production than is dissolved inorganic nitrogen (DIN). They therefore considered a TN criterion to be more appropriate than a DIN criterion for preventing impacts by inorganic nitrogen pollution in aquatic ecosystems. Camargo and Alonso (2006) believed that TN levels lower than the range 0.5–1.0 mg/L might prevent aquatic ecosystems (excluding those ecosystems with naturally high N levels) from developing acidification and eutrophication.

In the lower Yellow River, TN was measured only in 2002, 2003 and 2004, so none of the data are Kjeldahl Nitrogen. NH_3-N data were available for all sites for the entire period of record, so these include data collected using GB 3838-88 prior to 2002, and GB 3838-2002 from 2002. For all stations, the time series of NH_3-N data did not show a change point at 2002, when the standard changed.

7.11.4 Method of assigning an annual score for water quality

The official target water quality grade for the lower Yellow River is Grade III. The concentration value of each parameter tested, for each monthly sample, can be compared with the limits associated with each grade in GB 3838-2002. Thus, each sample has a grade score for each parameter, and the overall grade for the sample is the worst grade score. If a river has particular water quality problem, that parameter will tend to control the overall score. For some water quality parameters, the concentrations are partly controlled by natural characteristics, mainly the geology, which means that spatial variations can be expected independent of human disturbance.

GB 3838-2002 is a national standard, so it cannot account for local peculiarities associated with natural characteristics. The Yellow River has the highest total phosphorus concentrations of any river in the world. But this does not necessarily mean that there is a large concentration of bio-available phosphorus that would present a problem for eutrophication, as the majority of the P is associated with particulate matter (silt and clay sourced from the Loess Plateau). Thus, the TP limits in GB 3838-2002, which are similar to those for Australian rivers [which have low sediment concentrations and loads on a global scale (Rutherfurd and Gippel, 2001)], are probably too strict for the lower Yellow River. In other words, it would be impossible for the lower Yellow River to regularly achieve Grade III standards for TP, especially when one objective of management is to routinely de-silt Xiaolangdi Reservoir, and scour the bed of the channel. This is a reasonable argument for not including TP when calculating the overall grade of a water quality sample. The TP data can be investigated separately, along with suspended solids concentration data, and temperature data (both of which do not have a simple 5-grade scale in GB 3838-2002). Another reason for excluding TP from the analysis of overall water quality grade score for the lower Yellow River is that TP was not measured until 2002 at three of the four stations, and not after 1999 at the other (Figure 69), and given the known issue with high TP concentrations, its inclusion would create an artificial change point in the trend at 2002.

Total nitrogen was measured only in 2002, 2003 and 2004 at three of the four stations, and 1994-1997 at the other (Figure 69), so for the purpose of examining the pattern of overall water quality from 1994 to 2009 it would be unreasonable to include these data. However, it is worth noting that every TN measurement in these records fell into Grade V (between 1.5 and 2 mg/L). Using long-term nitrogen data not available to this study, several authors have unequivocally demonstrated that since the 1980s nitrogen levels in the lower Yellow River far exceeded the normal standards for protection of aquatic ecosystems (Xia et al. 2002; Chen et al. 2004; Fan and Huang, 2008; Yu T et al. 2010).

The approach taken to assigning an annual grade for water quality was as follows:

1. **Set the water quality management target grade**
   The official management target is Grade III for all stations. This analysis also set Grade II as a target for reduced risk to aquatic health.
2. **Decide which parameters will be included in the overall assessment**
   All parameters except TN and TP were included for the Grade III (human uses) assessment. All parameters except TN, TP and Faecal coliform were included for the Grade II (aquatic health) assessment.
3. **Set the water year**
   In the lower Yellow River the water year that fully contains the low flow period and high flow period is from December to November of the following year (see Hydrology section of this report).
4. **Set the seasons**
   In the lower Yellow River, splitting the year into two-6 month periods based on hydrological characteristics gave the high flow season as June to November and low flow season as December to May (see Hydrology section of this report).
5. **Determine the grade score for each month in the record, assessed over all included parameters**
7. **Count the number of months that met the target grade (or better) for each year.**
8. **Express the result as a proportion of the time that the target grade (or better) was met (score range of 0– 1)**
   Perform this calculation for the high flow season, the low flow season, and the entire year.

7.11.5 Trend in annual water quality score

The management target Grade III was achieved 30–80 per cent of the time prior to 1999 (Figure 70). There was no marked difference in the per cent of time the target was achieved between high flow and low flow seasons. Year 2000 was the worst year for water quality. From 2003 onwards, water quality showed an improving trend, although the improvement in low flow season water quality was delayed a further year. The most recent data show high rates of compliance with the Grade III standard, with annual achievement being 90 per cent of the time at all stations (Figure 70).

Setting the target grade to Grade II (a standard that offers a lower risk to the health of the aquatic environment), gave an entirely different trend in water quality (Figure 71). The percentage compliance was low for the entire period, for both low flow and high flow periods. The most recent data show annual achievement being only 10– 20 per cent of the time (Figure 71). These data strongly suggest that water quality is limiting river health.

Figure 70. Time series of per cent of time that water quality Grade III was achieved on the lower Yellow River from 1994–2009.

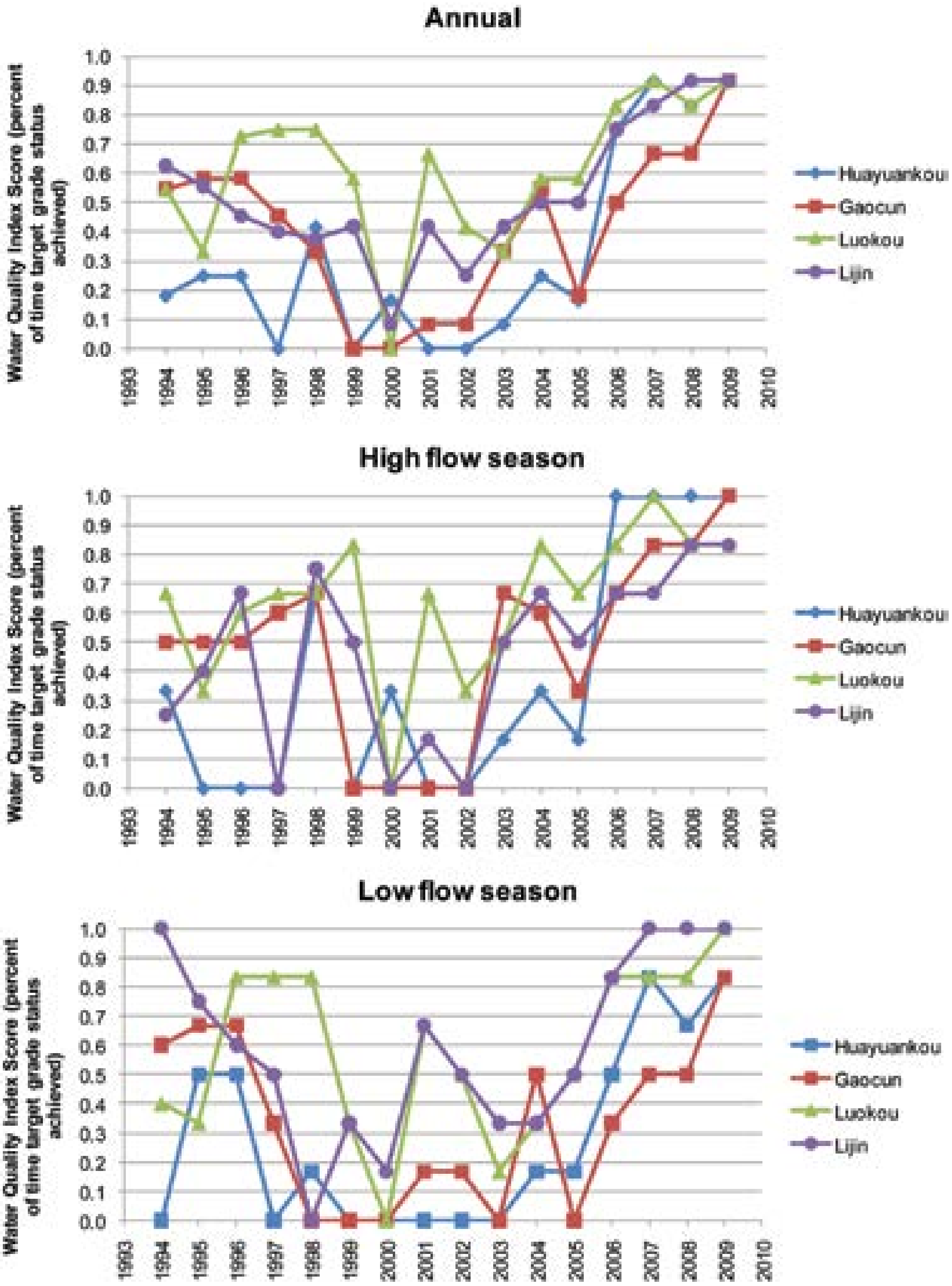
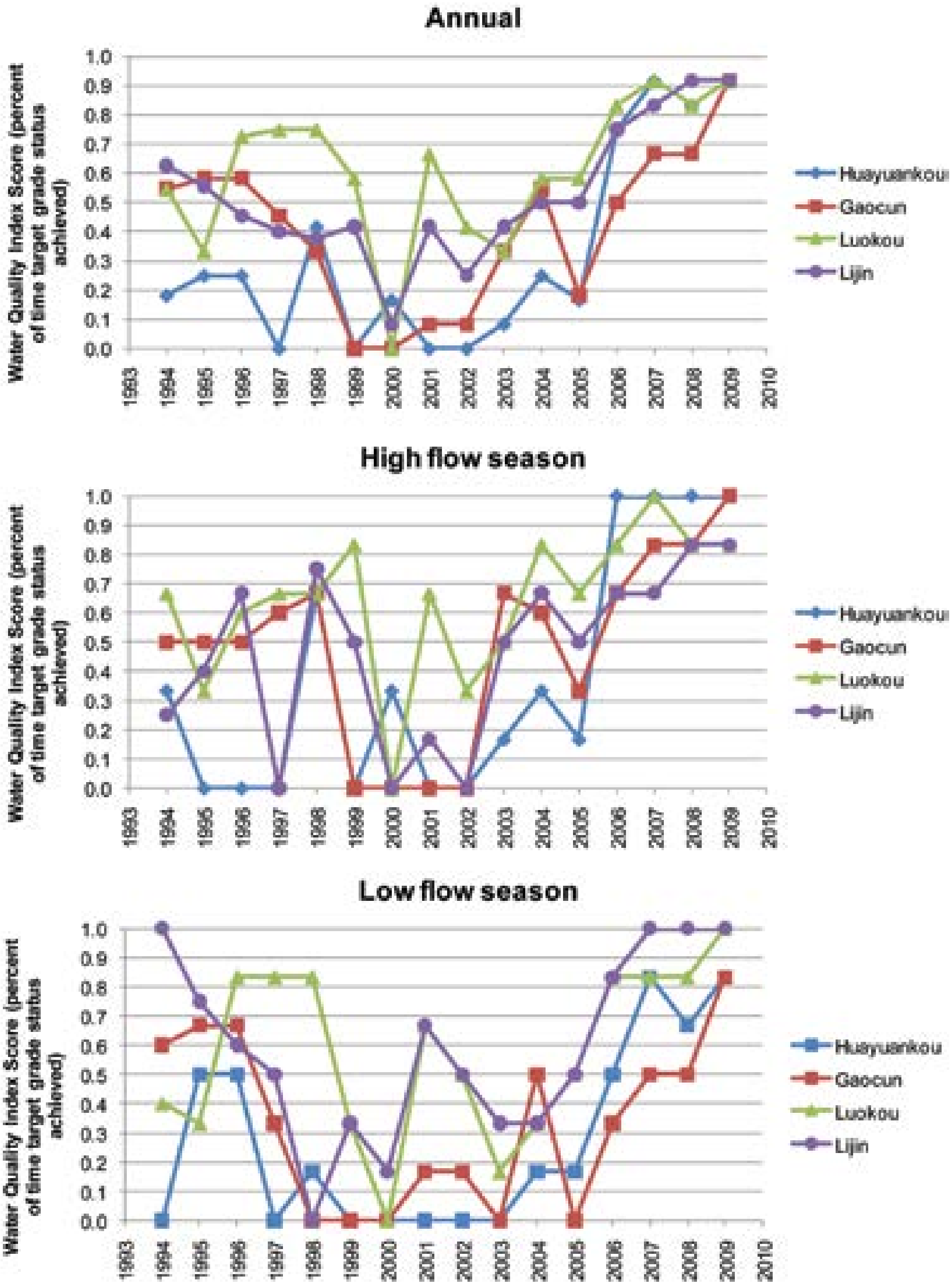


Figure 71. Time series of per cent of time that water quality Grade II was achieved on the lower Yellow River from 1994–2009.

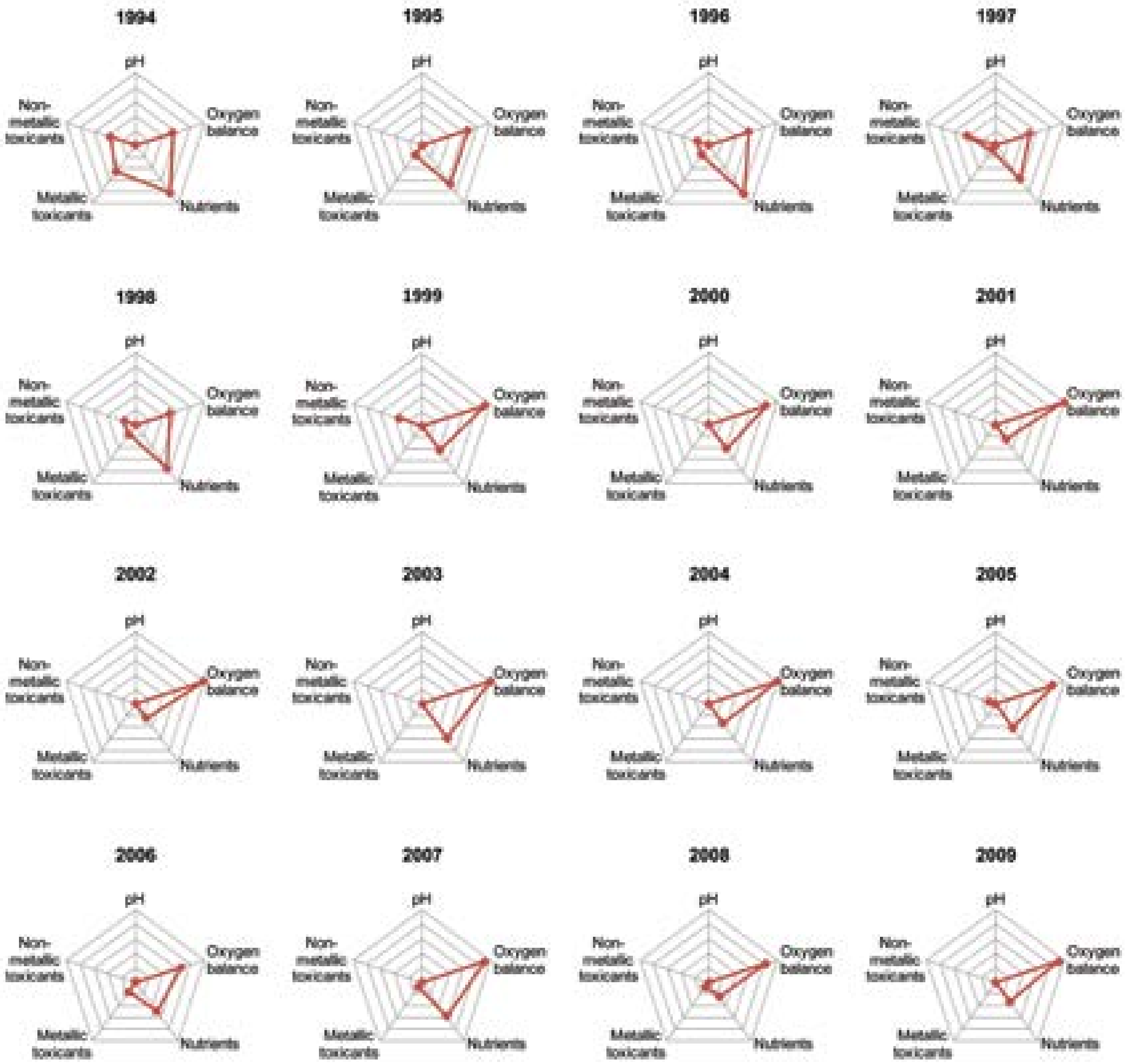


7.11.6 Limiting parameters for water quality grade

For every month, one or more parameters limit the grade to which the overall water quality will be assigned. These limiting parameters could be regarded as the main management priority, because lowering their concentration (or increasing it in the case of DO) would result in a step-wise improvement to the next grade. When classified by the main water quality categories (Table 23), patterns emerge in the limiting factors (Figure 73, Figure 74 and Figure 75):

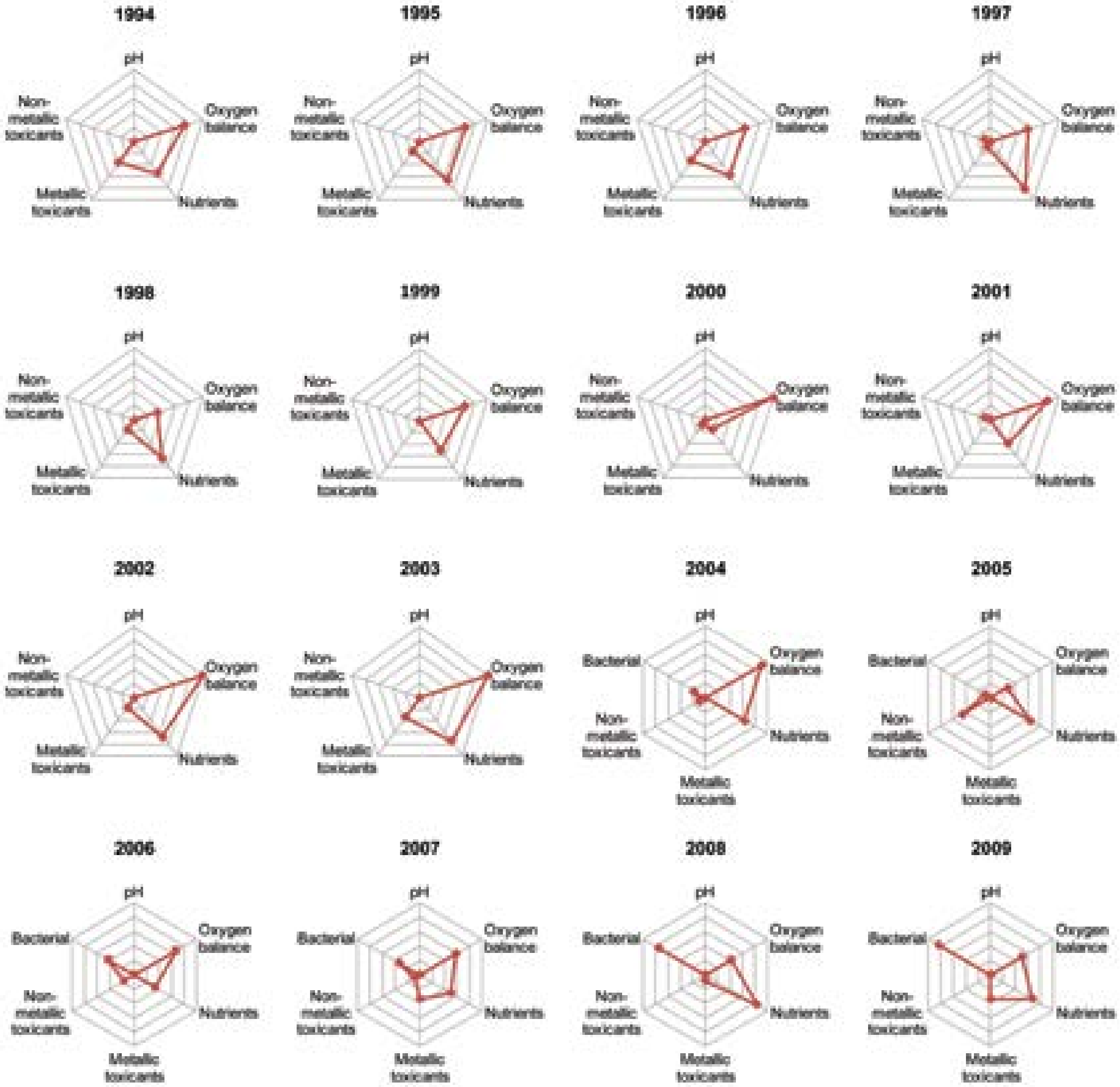
- **Oxygen balance**
  Oxygen balance was limiting throughout the entire period from 1994–2009 for all stations. COD was the most common limiting parameter in this group, with DO being the least frequent limiting parameter.
- **Nutrients**
  Nutrients were consistently limiting at all stations. In this analysis the only nutrient included was ammonia nitrogen. Had TP been included it would have limited the grade in nearly every month. Luokou and Huayuankou have seen a possible lessening of the frequency of NH3-N being limiting over time, but there has been no such trend at Gaocun and Lijin.
- **Metallic toxicants**
  From 1994–2002, metallic toxicants were frequently limiting at Gaocun, Luokou and Lijin, but less so at Gaocun, with the main problem metals being Cu, Zn and Pb. Metallic toxicants were not often limiting at Huayuankou. There was a Cd and Pb contamination spike at Luokou in September 2003 that did not appear at the other stations. Mercury (Hg) was occasionally limiting at Gaocun, Luokou and Lijin from 1994–1998, but then it ceased to be a problem until recently. Of concern was the reappearance of Hg as a limiting parameter at Gaocun and Lijin since 2007 and at Luokou since 2006.
- **Non-metallic toxicants**
  The non-metallic group of contaminants were not often limiting, but petroleum (oil) was a problem at Gaocun, Luokou and Lijin over the period 2003 to 2007. Petroleum was also a problem at Lijin from 1995 to 1997, and Huayuankou from 1996 to 1999 (petroleum data were not available for Gaocun and Luokou prior to 2000).
- **pH (relative acidity)**
  The pH of the water was always within the bounds of the standard, and so never limited the grade.
- **Bacterial**
  Faecal coliform data did not become available until 2003 at Loukou and 2004 at Gaocun and Lijin (it has never been monitored at Huayuankou). Since that time, this parameter frequently limited the grade. At each station, since monitoring began, the frequency of faecal coliform limiting the grade has markedly increased over time. In recent years it was the most common limiting parameter at the three monitored sites. Faecal coliform is a problem for human uses of the river, but not for the aquatic ecosystem.

Figure 72. Time series of the per cent of time one or more parameters from the main parameter classes limited the water quality grade at Huayuankou.



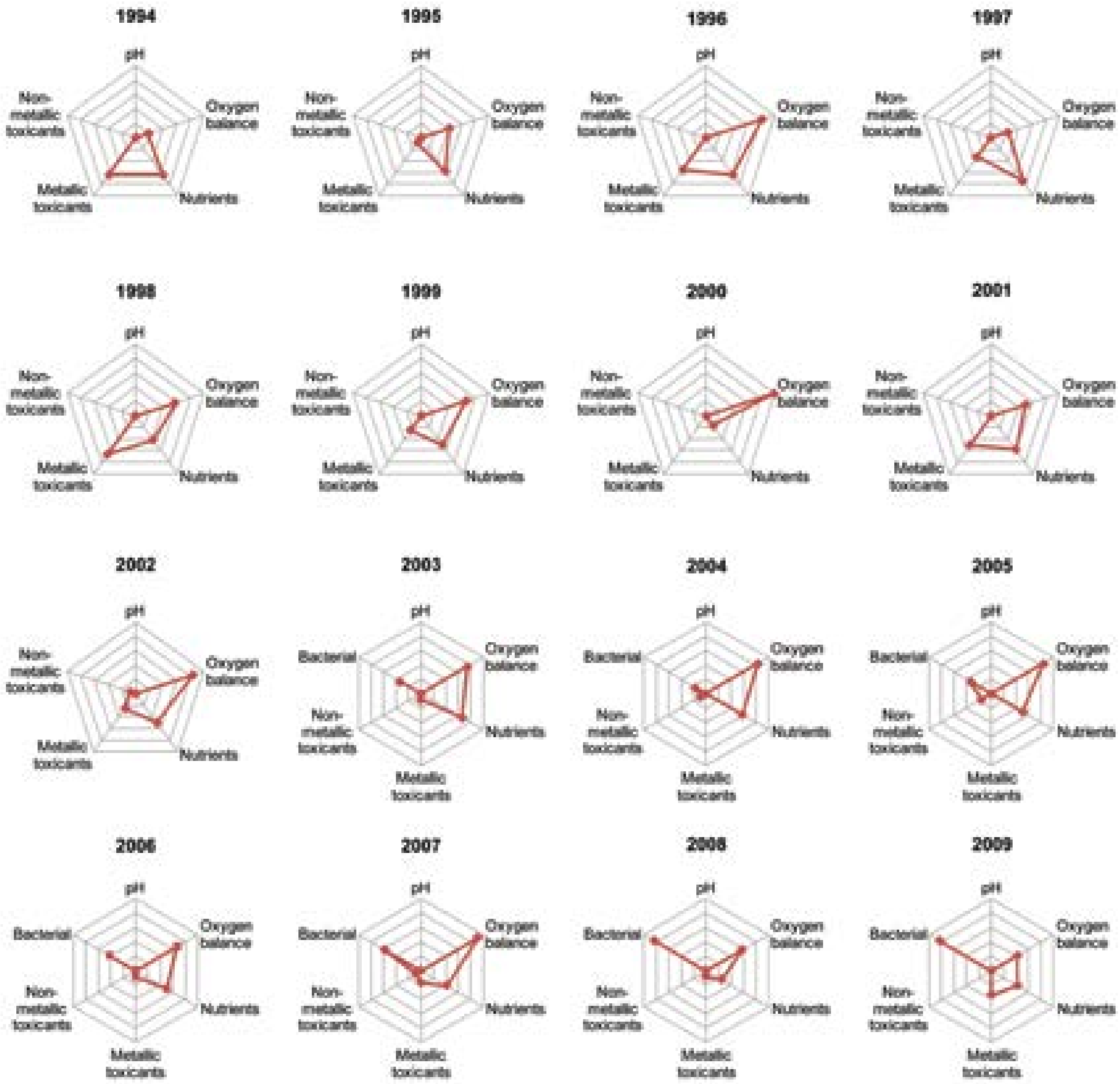
Note: The centre of the polygons is zero, and the outside is 100 per cent of months.

Figure 73. Time series of the per cent of time one or more parameters from the main parameter classes limited the water quality grade at Gaocun.



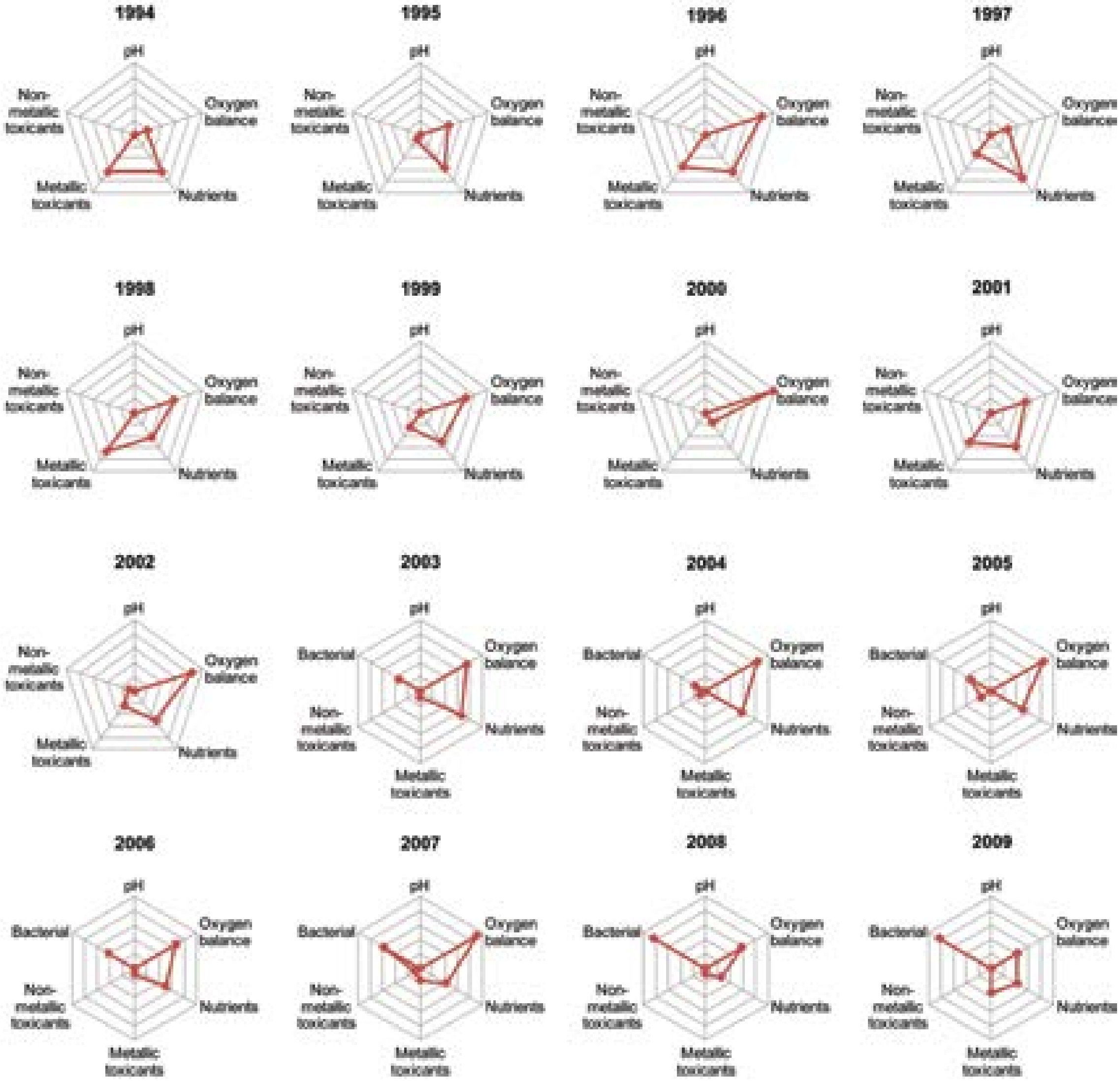
Note: The centre of the polygons is zero, and the outside is 100 per cent of months.

Figure 74. Time series of the per cent of time one or more parameters from the main parameter classes limited the water quality grade at Luokou.



Note: The centre of the polygons is zero, and the outside is 100 per cent of months.

Figure 75. Time series of the per cent of time one or more parameters from the main parameter classes limited the water quality grade at Lijin.



Note: The centre of the polygons is zero, and the outside is 100 per cent of months.

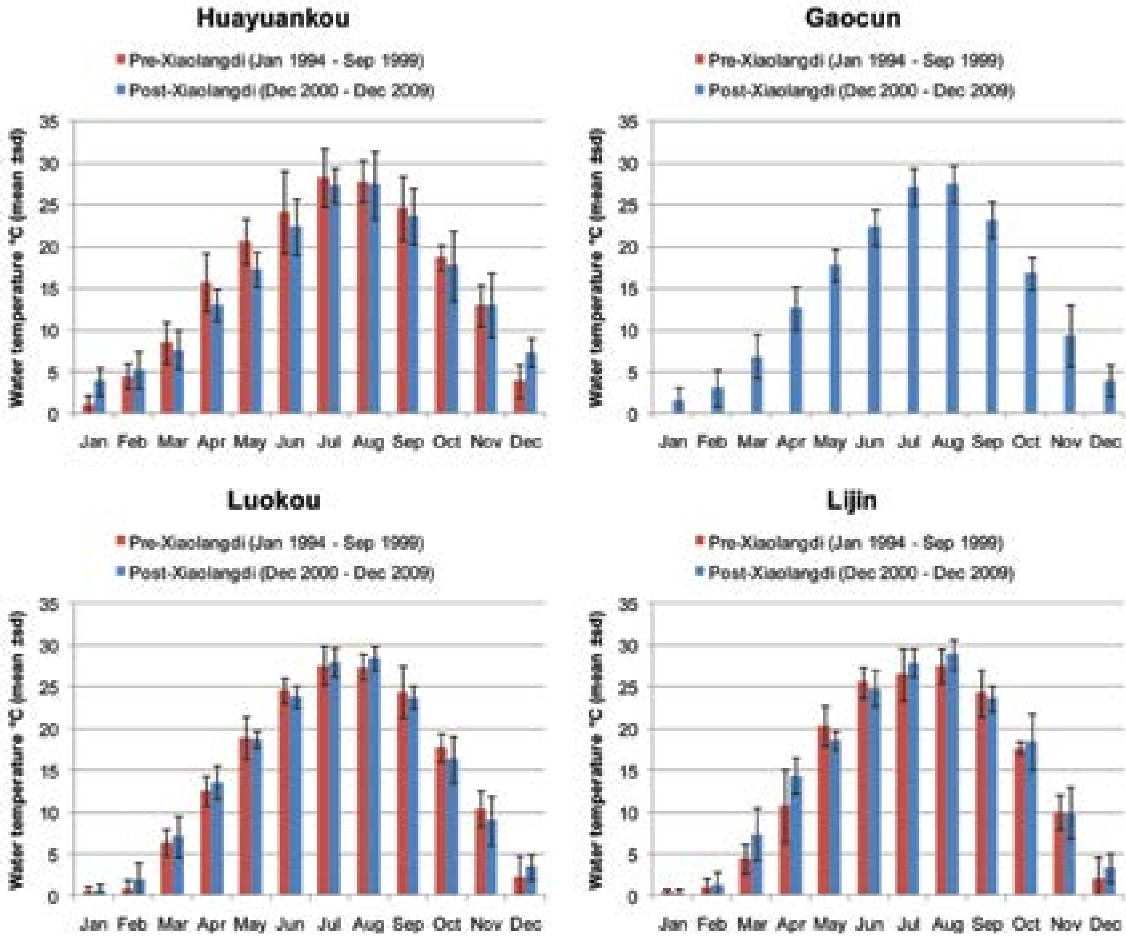
7.11.7 Water temperature

The Chinese water quality standard GB 3838-2002 states that human actions should cause an increase of less than 1°C/week and a decrease of less than 2 °C/week. This standard is difficult to apply to the lower Yellow River because the main impacts on water temperature are by: (i) dam construction and operation, which has a sudden and usually irreversible impact on downstream water temperatures, and (ii) shallowing of the flow depth due to lowered flow rates, which can cause the river's temperature to become more responsive to local air temperature and radiation.

From an ecological health perspective, water temperature is usually considered with respect to thresholds required for certain ecological processes to proceed, such as fish spawning. Most fish species in the Yellow River spawn in the period May to July, when temperatures rise to various thresholds in the range 15 to 20°C. From the perspective of human uses of the river, temperature is probably most critical with respect to the risk flooding from ice-dam formation. Risk of ice-dam formation is inversely related to air temperature, water temperature and flow rate (Qian D et al. 2007).

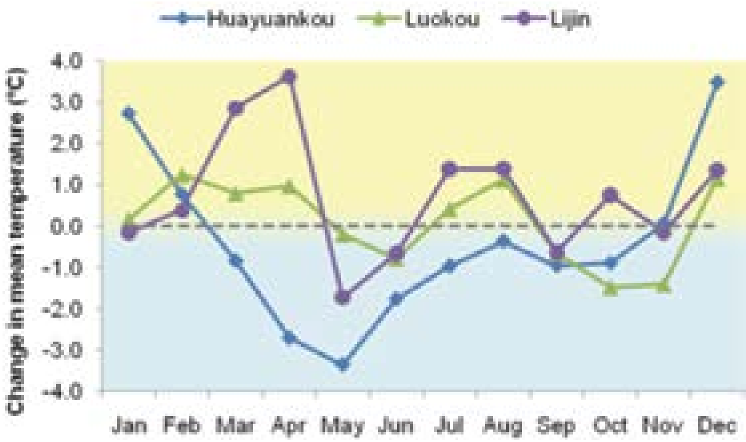
In the pre-Xiaolangdi dam period, mean water temperatures in May were 18–20 °C (Figure 76), which suggests that temperature did not often limit fish spawning. In the post-Xiaolangdi dam period, the spring water temperatures were reduced, to the extent that spawning of some species could have been delayed by a few weeks in some years (Figure 76). April, May and June were particularly impacted at Huayuankou (Figure 77). The impact was less downstream at Luokou and Lijin (Figure 77). Winter temperatures have risen post-Xiaolangdi Dam, particularly in December, and particularly at Huayuankou (Figure 76 and Figure 77), lowering the risk of ice-dam formation.

Figure 76. Monthly distribution of water temperature for pre- and post-Xiaolangdi Dam periods (based on monthly sampling).



Note: Pre-Xiaolangdi Dam data were not available for Gaocun.

Figure 77. Monthly distribution of change in mean water temperature from pre- to post-Xiaolangdi Dam periods.



Note: Pre-Xiaolangdi Dam data were not available for Gaocun.

7.11.8 Total suspended solids concentration

The Chinese water quality standard GB 3838-2002 does not include criteria for total suspended solids concentration (TSS). The limits on TSS (or turbidity) for ecological health applied elsewhere in the world are likely to be inappropriate for the lower Yellow River, given that historically it was one of the most heavily sediment laden rivers in the world.

It would be expected that the species found in the lower Yellow River are tolerant of high TSS. The only data in the literature regarding tolerances of lower Yellow River fish to TSS concerns Yellow River carp (*Cyprinus carpio*). Wang and Yang (1986) suggested that TSS exceeding 40 kg/m^3 (g/L) were lethal to the Yellow River carp, although Panek (1987) quoted a significantly higher figure of 165 kg/m^3 (g/L).

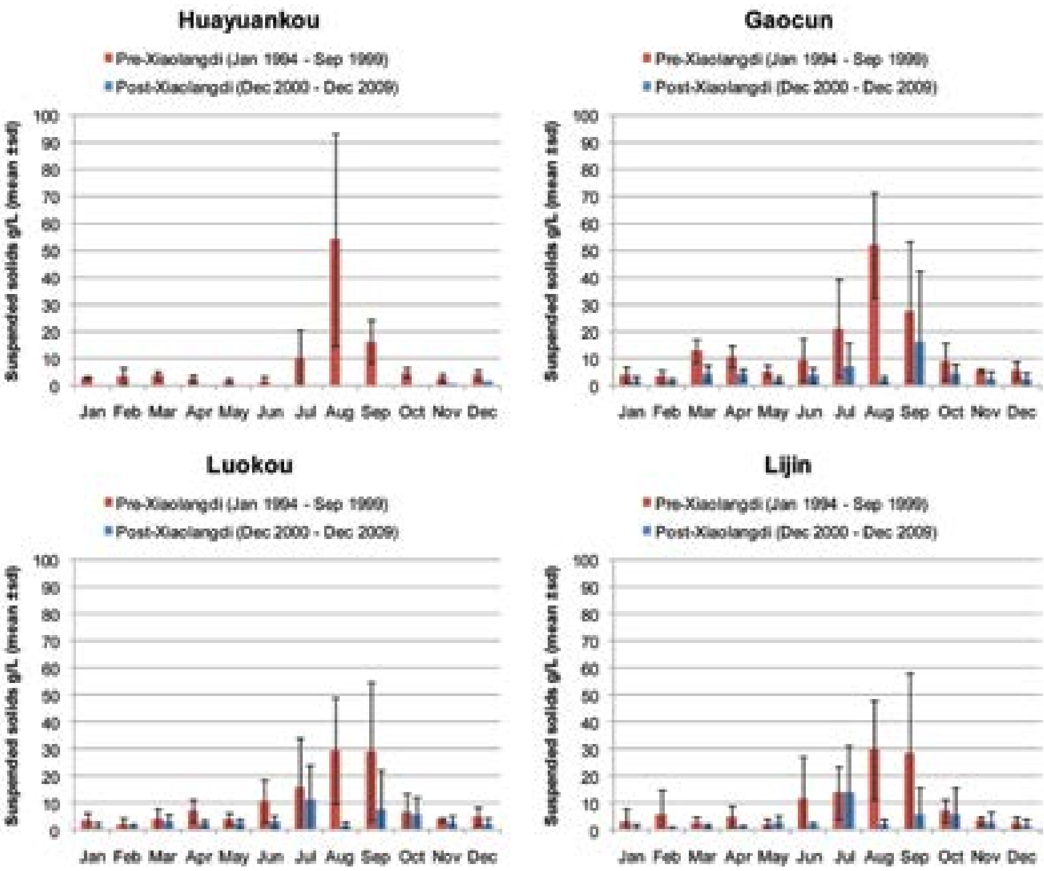
Nutrient concentrations, and the concentrations of many other contaminants, are directly related to TSS (due to preferential adsorption of contaminants onto the fine-grain suspended particles), so a reduction in TSS would be positive from the perspective of overall water quality.

The depth to which light can penetrate the water column (the euphotic depth) is directly related to TSS, and this depth is an important determinant of primary productivity. This is especially the case in the lower Yellow River, where nutrients are not limiting to algal growth. Thus, a reduction in TSS would be positive from the perspective of primary productivity.

In the pre-Xiaolangdi Dam period, TSS was high in the summer months, especially July, August and September (Figure 78). The peak concentrations were lower at the downstream stations of Luokou and Lijin, but here elevated TSS was spread over a longer season (Figure 78). TSS often exceeded 40 g/L in summer, so it would appear that Wang and Yang (1986) under-estimated the TSS tolerance limit of Yellow River carp. The post-Xiaolangdi Dam period was characterised by reduced TSS in most months, but especially in August and September, with the relative reduction being higher closer to Xiaolangdi Dam (Figure 78 and Figure 79). These data suggest that, post-Xiaolangdi Dam, water clarity has increased, which could:

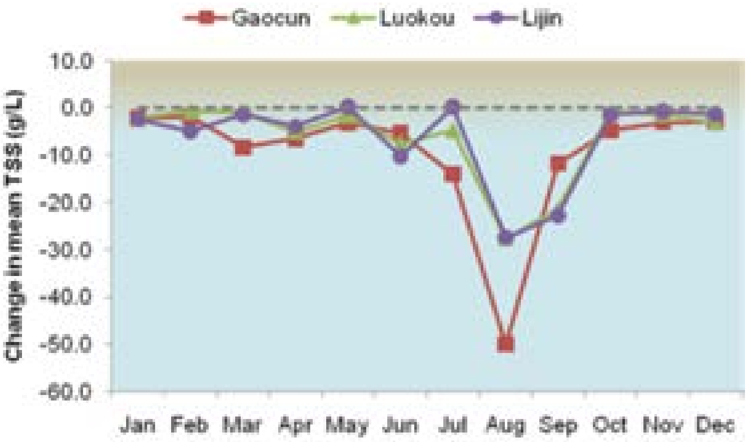
- be disadvantageous for species advantaged by highly turbid conditions,
- play a role in general water quality improvements, and
- lead to higher rates of primary production, especially in summer.

Figure 78. Monthly distribution of total suspended solids concentration for pre- and post-Xiaolangdi Dam periods (based on monthly sampling).



Note: Post-Xiaolangdi Dam data were not available for Huayuankou.

Figure 79. Monthly distribution of change in total suspended solids concentration (TSS) from pre- to post-Xiaolangdi Dam periods.



Note: post-Xiaolangdi Dam data were not available for Huayuankou.

7.11.9 Water quality-flow relationships

From 1994 to 1999, before Xiaolangdi Dam began operation, water quality showed a generally declining trend, while after Xiaolangdi Dam began operation water quality showed a generally improving trend (Figure 70). The reasons for a poor or good water quality index score can be complex, but the improvements in water quality since 2002, and particularly since 2004, appear to be associated with raising the baseflows (Figure 6). As baseflow occurs for most of the time, a baseflow index is more likely to be correlated with monthly water quality data than an event index.

Using the daily baseflow series (derived using the digital filter), the median daily baseflow was calculated for each year, for both the high flow (June–November) and low flow (December–May) seasons. These baseflow data were then plotted against the corresponding water quality index scores, for the pre-Xiaolangdi Dam period (Figure 80) and the post-Xiaolangdi Dam period (Figure 81). The data were split in this way because Xiaolangdi Dam resulted in a significant reduction in total suspended solids concentration (Figure 78 and Figure 79), which can impact many water quality parameters, and because Xiaolangdi Dam was operated to increase baseflows in the river (Figure 6).

For the pre-Xiaolangdi Dam period, water quality index score and baseflow index value were not correlated, except at Lijin, in particular for the low flow season (Figure 80). For the post-Xiaolangdi Dam period, there were significant correlations between water quality index score and baseflow index value (Figure 81), although there were outliers, in particular 2004, which had relatively high baseflows but poor water quality. Over the post-Xiaolangdi Dam period, improvement in water quality index scores to values of 0.5 or better were associated with baseflows of approx. >500 m^3/s at Huayuankou, approx. >450 m^3/s at Sunkou/Gaocun, approx. >300 m^3/s at Luokou, and approx. >200 m^3/s at Lijin (Figure 81). These are very general empirically derived values that should not be interpreted as flow recommendations.

Figure 80. Relationships between median baseflow of the low flow season months (Dec–May) and the high-flow season months (Jun–Nov) for each year from 1994–1999 (pre-Xiaolangdi Dam) and the corresponding water quality index score.

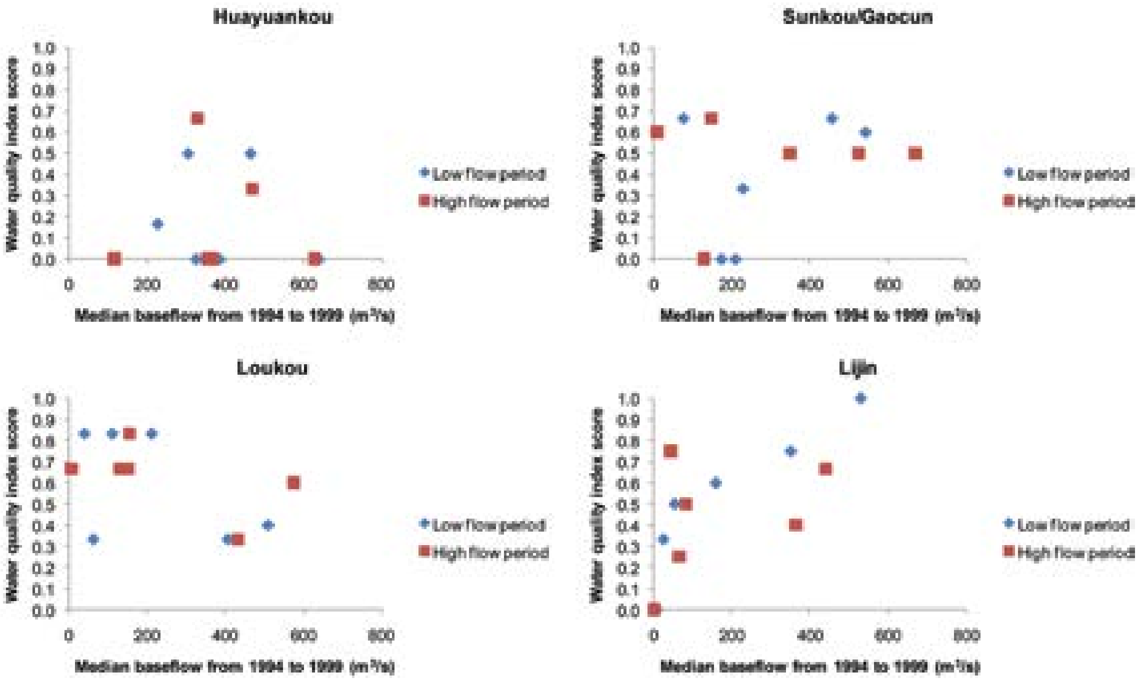
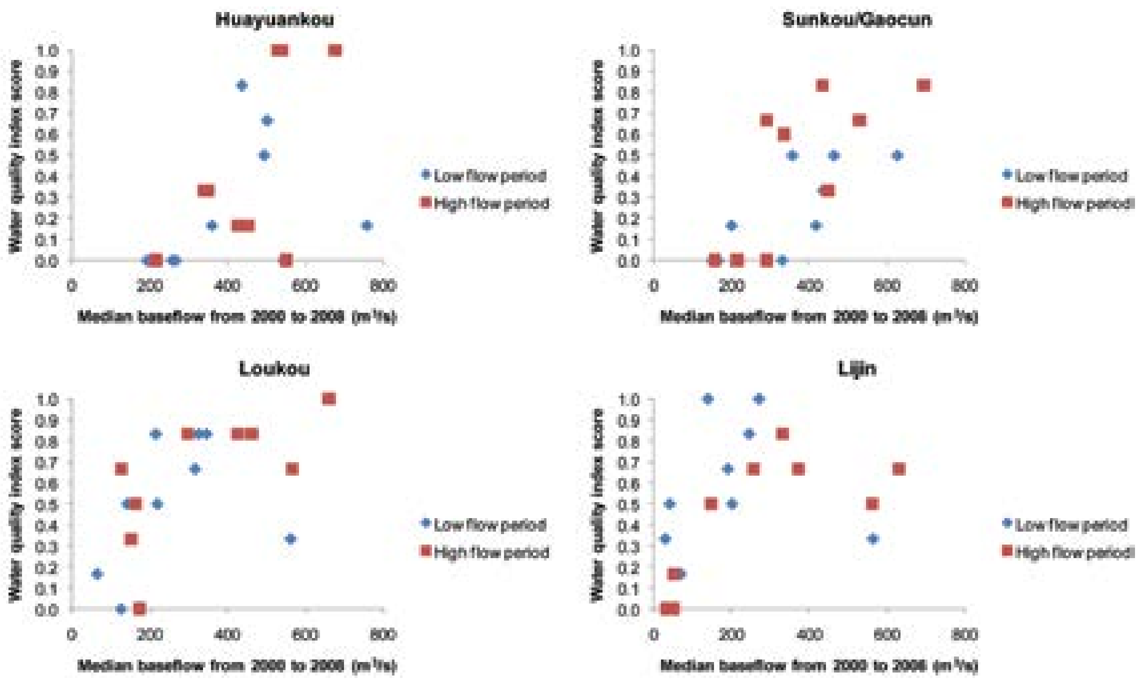


Figure 81. Relationships between median baseflow of the low flow season months (Dec–May) and the high flow season months (Jun–Nov) for each year from 2000–2008 (post-Xiaolangdi Dam) and the corresponding water quality index score.



7.12 Water quality flow objectives

In the lower Yellow River it is apparent that water quality is dependent on three main factors:

- The load of contaminants input to the river along it course, from agricultural outfalls, sewerage discharges, urban runoff, and industrial discharges. These loads are partly related to flow, as the runoff from agricultural and urban areas is higher in wetter years, but fundamentally, these loads are related to pollution control policies.
- The TSS concentration, which controls the concentration of many other pollutants. There is an indication in the data that retention of water high in TSS in Xiaolangdi reservoir during the high flow season has been a factor in the observed improvements in water quality since 2000.
- The discharge, particularly the baseflow discharge, which acts to dilute pollutants. There is an indication in the data that release of increased baseflows from Xiaolangdi Dam has been a factor in the observed improvements in water quality since 2000.

The Scientific Panel for this project did not undertake an independent assessment of the flows required to achieve a given water quality grade in the lower Yellow River. The current target for the lower Yellow River is Grade III, which according to the Chinese standard GB 3838-2002 is adequate for most human uses, but is marginal for ecological health (Table 22).

The Scientific Panel for this project was of the opinion that some of the criteria in GB 3838-2002 may be inappropriate for Chinese rivers with very high suspended sediment loads, such as the lower Yellow River. Also, GB 3838-2002 is a comprehensive standard, meant for application to many different forms of river utilisation, so it cannot be regarded as an ideal standard for river health assessment. There is clearly a need to develop a set of standards for river health assessment that are specific to Chinese rivers (Wu et al. 2010). Such a standard may require different criteria values for the main eco-hydrological regions of China.

It would appear that the ecological health of the lower Yellow River remains limited to some extent by impaired water quality. Dilution of contaminated water is one approach to this problem, while the other is to address the problem at its source. This issue was considered beyond the scope of the present study, so the Scientific Panel simply adopted the highest of the recommendations made by Ni and Qian (2002), Hao et al. (2005), Liu et al. (2006) and Liu et al. (2008). This gave minimum flows of 300 m^3/s at Xiaolangdi, 320 m^3/s at Huayuankou, 234 m^3/s for Huayuankou-Gaocun reach, 146 m^3/s for Gaocun-Aishan reach, and 60 m^3/s for Lijin (Table 27).

While it has been established that the TSS and water temperature changed significantly following construction and operation of Xiaolangdi Dam, there are no data available concerning the possible impact these changes might have had on the ecology of the river. Temperature has become colder in spring, and warmer in winter, while TSS has declined in most months, especially in the summer high flow season. It is possible that spawning has been delayed for some fish species, and conditions would have become more or less favourable to certain species, depending on their turbidity tolerances and preferences. The effectiveness of environmental flows may rely to some extent on providing appropriate spring water temperatures, and appropriate turbidity levels (Table 27).

Chapter 8. Waterbirds

8.1 Introduction

Waterbirds constitute an important component of the Yellow River aquatic ecosystem; they require the maintenance of suitable foraging, refuge and breeding habitat. In addition, many terrestrial bird species, particularly insectivores, are also reliant on wetland productivity. In the long term, abundant and diverse native bird populations are indicative of wetland health, as birds require both sufficient food resources and nesting habitat, which generally equate to a healthy wetland (Reid and Brooks 2000).

Birds that depend on the flow regime of the Yellow River and associated wetlands can be broadly split into four groups based on when they are present at the site:

- summer breeding migrants which migrate north to breed in spring and summer, before departing south again in autumn to avoid the colder period of the year
- winter migrants seeking refuge from the more extreme climate to the north
- transient spring (northward moving) and autumn (southward moving) migrants
- resident species.

Of the 98 waterbird species found by Ma et al. (2007) at Mengjin wetlands from 1995–2008, 41 species were winter migrants, 32 species were summer migrants, 16 species were transient, and nine were residents.

Most waterbirds depart the region over the winter as the Yellow River lies north of the average January 0°C isotherm (Liu 1997). Consequently many of the associated wetlands are often frozen during the non-breeding season.

Members of the family Anatidae are numerically a major component of the wintering waterbird community in eastern China and around the lower Yellow River, with shorebirds, gulls, terns, herons and egrets the other main groups present. Foraging guilds present in the waterbird community at this time include sedge/grass eating birds (e.g. Bean Goose and greater white-fronted goose), aquatic vegetation/seed eaters (e.g. Falcated Duck, Baikal Teal, Spot-Billed Duck), invertebrate consumers (e.g. shorebirds, Eurasian Spoonbill) and tuber eaters (e.g. Swan Goose, Tundra Swan and Hooded Crane) (Cheng 2009).

The bird community associated with a floodplain, riparian zone, and wetlands is complex and diverse. A large number of species make use of the area in differing ways and are reliant upon inundation of the floodplain and wetlands and the presence of healthy floodplain and riparian vegetation as the basis of the community. The ecological impact of reduced floodplain inundation, as a result of river regulation, may have been significantly underestimated around the world (Ballinger and Lake 2006).

Changes to the extent and nature of movement of energy and nutrients from riverine wetlands to the surrounding terrestrial landscape will significantly impact on the productivity of linked terrestrial fauna communities.

Table 27. Water quality-based objectives and flow requirements. WSDR is water sediment discharge regulation.

No.	Objective	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing	Reach
WQ1	Dilute contaminants to Grade III standard	Low flow and high flow	≥ 320 m3/s	≥ 90% of time	≥ 75% of the time	All year	Reach 1
WQ2	Dilute contaminants to Grade III standard	Low flow and high flow	≥ 234 m3/s	≥ 90% of time	≥ 75% of the time	All year	Reach 2
WQ3	Dilute contaminants to Grade III standard	Low flow and high flow	≥ 146 m3/s	≥ 90% of time	≥ 75% of the time	All year	Reach 3
WQ4	Dilute contaminants to Grade III standard	Low flow and high flow	≥ 60 m3/s	≥ 90% of time	≥ 75% of the time	All year	Reach 4
WQ5	Temperature within range of tolerance of biota, especially fish spawning	Low flow, high flow, pulses and bankfull	As required (see fish objectives)	≥ 90% of time	≥ 75% of the time	All year (esp. May-Aug)	All reaches
WQ6	Total suspended solids concentration within range of tolerance of biota, and within pre-dam range	Low flow, high flow, pulses and bankfull	WSDR event peak ≤ 110 kg/m3 (g/L)	≥ 90% of time	≥ 75% of the time	June-Aug	All reaches

8.2 Waterbird foraging habitat

Within the Yellow River system, and its associated wetland complexes, a variety of foraging microhabitats are available for birds under natural flow conditions. For a complex bird community to exist in an area, the foraging habitat requirements are diverse; a mosaic of wetlands types varying in such characteristics as margin slope and water depth, a variety of temporal and spatial flow patterns, and an associated variety of vegetation types both in the water and the riparian zone are required. Natural or artificial waterbodies that offer a variety of water depths and vegetation communities tend to have rich communities of invertebrates, and carry higher numbers of species and individuals of waterbirds (Broome and Jarman 1983).

Wetlands often support species of waterbirds that have diverse physical adaptations to feed on a wide variety of food types, with the composition and abundance of waterbird communities on a wetland often reflecting the availability (type and quantity) of food (Kingsford and Porter 1994; McDougall and Timms 2001). The feeding behaviour of waders is closely associated with their bill size and shape. Generally short-billed species are ‘pickers’, mostly taking food items from the substrate surface (e.g. plovers), while those with long bills feed by probing deeply into substrates (e.g. curlews). Those with medium length straight bills are often generalists, able to feed by picking or probing. In addition, there are a number of specialist feeders with bills adapted to either their preferred food (e.g. oystercatcher) or their primary feeding technique (e.g. spoonbills). Many waterbirds can adapt their feeding behaviours allowing them to access a variety of food sources, if the opportunity arises, or if conditions do not allow their usual feeding methods (Chandler 2009). Wader distributions and densities often reflect the availability of preferred prey species, both in terms of prey species abundance and the ability of birds to access prey. The latter is a function of physical foraging habitat, such as preferred water depths of substrate types. Habitat use can be influenced by the proximity of roost sites, water quality (especially salinity), the availability of preferred habitat, and the need for refuge.

Waterbird foraging habitat within the Yellow River, associated wetland and floodplain elements, and estuary, broadly consists of: flowing water, deep water (>0.3 m deep); shallow water (0–0.3 m deep); areas inundated during tidal flows and with wind seiche; emergent and fringing vegetation; mud and sand flats; saltmarsh; and supratidal or flood zones.

8.2.1 Flowing water

Managed flow variability in a stream often has the unintended outcome of ecological degradation in a stream through loss of key natural flow elements (Richter et al. 2003). Natural freshwater ecosystems are strongly influenced by specific facets of natural hydrologic variability. Of particular importance are seasonal high and low flows, and occasional floods and droughts (Richter et al. 1997). Modification of a river’s natural flow variability can result in changes in the physical (e.g. simplified physical structure of channel and floodplain), chemical (e.g. modified water chemistry and temperatures), and biological (e.g. lower native species diversity and modified abundance and distribution of species) conditions and functions (Richter et al. 2003).

Some waterbird species have specific flow requirements. For example in the lower Yellow River region the common kingfisher *Alcedo atthis* is found in habitats where the velocity is nil or very low, while the crested kingfisher *Megaceryle lugubris* prefers cold fast flowing streams (Brazil 2009).

8.2.2 Deep water (>0.3 m deep)

In waterbodies that are permanent or wet for long periods of time, algae, epiphytes, macroinvertebrates, zooplankton, and fish found through the water column and in the vegetation beds together constitute a complex food web supporting a variety of birds (Paracuellos 2006). Maintenance of permanent water within a perennial wetland complex is consequently important.

Most wading birds use water up to 30 cm deep, generally walking on the substrate as they forage. Other species, and some of the waders, forage in deeper water either for similar food sources found on or near the surface, or for alternative food sources in the deeper water column and on the substrate.

A range of waterbird feeding guilds use deep, open, water particularly diving waterbirds (Broome and Jarman 1983). Deep diving ducks such as Baer's Pochard feed on insects, molluscs, shrimps, fish and algae during the breeding season, and aquatic plants and seeds, and the Tufted Duck feed mainly on molluscs, crustaceans, and aquatic insects, as well as grain and the seeds and vegetative parts of aquatic plants. Fish-eating (piscivorous) birds may catch fish on the surface (e.g. Whiskered Tern), or may dive to catch fish and a range of invertebrates such as crustaceans (e.g. grebes and cormorants). Grazing waterfowl such as the Whooper Swans will upend and use their long neck to browse on plant material in deep water.

While larger birds will use deeper water to forage, they generally prefer shallow water when food is available (Gawlik 2002), as it requires less energy to obtain the available food (Lovvorn 1994).

Turbidity has implications for the diversity and abundance of food resources available in deeper water, with highly turbid water limiting the primary productivity to the upper parts of the water column or water-body fringes.

8.2.3 Intertidal and seiche zones

The substrate exposed and inundated through tidal movement in the Yellow River estuary, or through wind mounding of water (seiching), particularly in a shallow gently sloping bed of a larger water body, provides important foraging habitat for a wide variety of waterbird species. The force of wind moving over water can cause a surge of water, which can inundate the lee shore of a water body. The exposure and inundation of the substrate and vegetation along a shore by this process with change in wind direction, or by seiching (a short-period oscillation in an enclosed or semi-enclosed body of water), provides an important foraging habitat for many waterbird species.

Some species forage in the shallow receding or encroaching water, other species forage on the recently exposed sand or mud flats, and some forage at the moving interface of water over substrate as the water encroaches and recedes.

The state of the tidal cycle, or temporal and spatial pattern of water inundation and retreat, alters the area of habitat available for foraging waterbirds and also affects prey behaviour and substrate penetrability, which in turn affects the harvestability of prey or other food source such as tubers (Esselink and Zwarts 1989). Substrate type (e.g. mud, sand, rock) can affect the density of harvestable prey by affecting the prey's behaviour, for example by changing the depth to which they bury themselves, making them more or less susceptible to predation (Esselink and Zwarts 1989).

In tidal environments most shorebird species segregate themselves in intertidal habitat according to preferences for sedimentary penetrability and water depth. Around the Yellow River Delta the interplay between tidal flows, river flows, and sedimentation patterns provide extensive areas of foraging habitat for a diverse range of waterbird species, many of which merit significant national and international conservation ratings.

8.2.4 Supratidal and flood zones

Shallow flooding of wetlands, floodplains and deltas provides highly productive foraging habitat for waterbird species (Colwell and Taft 2000), and the associated marked increase in productivity is the basis of many waterbird reproductive events (Crome 1988; Junk et al. 1989; Scott 1997).

The cycle of growth and decay, and thus greater availability of nutrients in the water column (Baldwin and Mitchell 2000), resulting from inundation and exposure of vegetation along the river and wetland margins, is the basis of a complex food web that provides food to the vertebrates that forage in, on and around the water (Baxter et al. 2005).

Water bodies that are permanent, or ephemeral systems that lose their drying phase, have been shown to support a lower density and diversity of birds, have lower invertebrate productivity, and have higher abundance of introduced fish and rates of anaerobic decomposition of organic matter (Crome 1988; Kingston et al. 2004; Gawne and Scholz 2006).

Turbidity can also be affected, and this can lead to reductions in euphotic depth and primary productivity. For wetland ecosystems that have evolved in response to seasonal drying, permanent inundation would likely lead to ecological degradation and displacement by an alternative community of flora and fauna.

The Yellow River historically provided complex waterbird foraging habitat supporting a diverse range of species through two natural cycles of flooding and water level recession:

- Low-level spring snowmelt flow flooding with receding water levels in late spring early summer (see Figure 38, Figure 39, Figure 40 and Figure 41). This brief drop in water level prior to the much larger summer floods exposes mud flats and shallow water level areas in time for northward migrating birds in late spring (May).
- High-level summer monsoonal flooding followed by water level recession during the autumn and winter (see Figure 38, Figure 39, Figure 40 and Figure 41). These waters inundate the floodplain and associated wetlands and backwaters. Receding water levels around the edges of numerous shallow ephemeral wetlands create extensive areas of foraging habitat. This hydrological cycle creates ideal waterbird wetland foraging habitat with receding water levels exposing foraging habitat in time for southward moving migrant populations and to provide on ongoing food source for overwintering populations

Reduction in frequency and duration of flood events such as these would normally lead to reduced floodplain productivity, which in turn would lead to reduced supply of nutrients and carbon to the main river channel. Ultimately, this would lower productivity within the river. In the case of the lower Yellow River, although the nutrient levels are artificially high due to discharge of pollutants to the river, the turbidity is often relatively high, which would suppress primary productivity due to low depth of light penetration into the water column. In this case, carbon and nutrient wash-off from floodplains likely makes only a minor contribution to the process of primary productivity.

For the lower Yellow River across the flood zone, the productivity of the associated plant communities, particularly the sedge and grass components, is important to the sedge/grass eating guild of the waterbird community. Many of the overwintering Anatidae for example are reliant on the seeds produced subsequent to the summer floods to provide the food resources for the overwintering populations.

8.2.5 Shallow water (<0.3 m deep)

Wading birds predominantly forage in water depths up to approximately 30 cm. The water depth used by the different waterbird species when foraging is strongly linked with neck and leg length (Baker 1979; Zeffer et al. 2003), which dictates where a species will have the most success in foraging. Worldwide the greatest diversity and abundance of foraging waterbirds is found in water depths of between 10 and 20 cm (Isola et al. 2000; Taft et al. 2002). Natural or artificial water bodies that offer an array of water depths and vegetation associations tend to have rich communities of invertebrates, and carry higher numbers of species and individuals of waterbirds (Broome and Jarman 1983). Piscivores feed on fish in shallow water in preference to those in deeper water (Gawlik 2002). The density of prey at which the birds will stop searching for food increases with increasing depth; the value at 28 cm is almost double that at 10 cm (Gawlik 2002). Maximising the area inundated up to 30 cm in depth will enhance species diversity and numbers of waterbirds able to forage in a wetland complex.

Within the wetland and floodplain elements and estuary of the Yellow River, waterbirds, such as snipe, black-winged stilt, common moorhen, egrets, herons, spoonbills, bitterns, ibis, storks, a wide variety of ducks and geese, and shorebirds will feed predominantly in this zone.

8.2.6 Mud and sand flats

In wetlands, shallow inundation of mudflats facilitates ecosystem productivity and replenishes mudflat prey for waterbirds. Subsequent exposure and drying of the wetland sediments facilitates a suite of biotic and abiotic processes that do not occur in permanently inundated sediments. This cycle provides for a complex food web including food for the vertebrates that forage in, on and around the water (Baxter et al. 2005). This, in turn, sustains many species of fish and waterbirds by providing favourable conditions for breeding (Crome 1988; Junk et al. 1989; Scott 1997).

As wetland water levels drop, mudflat exposure ensures mudflat resources are available to waterbirds. With shallower water the fish community becomes more susceptible to avian predation.

The shores of the Yellow River Delta and estuary, shoreline of lakes, edges of the river and edges of many lateral wetlands are fringed at lower water levels by sand and mud flats of several metres to hundreds of metres in width. A community of invertebrate macrofauna is found living within and on these flats, providing the basis of a complex and productive food web under normal conditions. These extensive mudflats and shallow waters are particularly important for shorebirds. The tides, seasonal and annual changes in water level, and changes with flooding regime and wind direction, rainfall, and evaporation result in patterns of inundation and exposure that vary the accessibility and extent of this habitat available to shorebirds (Brookes et al. 2009). Reduced silt loads carried by the Yellow River under regulated flow reduce the aerial extent of mudflats in the river delta, and the nutrient supply to the associated food web, decreasing the waterbird biomass supported in the region.

Reduced flow reaching the delta and reduced temporal and spatial variability in flow mean that mud and sandflats may be exposed for longer periods of time, resulting in more solid surfaces, affecting the habitat selection and foraging success of waders, as pack depth and prey density depend on the penetrability of the sediment. Constriction of foraging habitat area has implications for the abundance of foraging birds in the Yellow River Delta.

8.2.7 Emergent and fringing vegetation

The presence of a healthy macrophyte community within and fringing a wetland or along the edges of a river is important as either a direct or indirect food source, and/or provides an essential refuge or roosting site. These vegetation communities support a distinct subgroup of waterbirds, e.g. many waterfowl, rails, bitterns, snipe, reed warblers and the Vinous-throated Parrotbill. For this group of waterbirds, use of an area is influenced by the structural and cover pattern of the vegetation emergent from the waterbody and around its fringe, rather and the actual plant species present.

For a complex bird community to exist in an area, the foraging habitat requirements are diverse, requiring a mosaic of shallow gently sloping margins as well as deep water and reed beds. Abundance of macroinvertebrates is usually positively correlated with macrophyte abundance and diversity (Boulton and Brock 1991; Hargeby et al. 1994; Safran et al. 2000). In wetlands, total and breeding waterbird species richness have been shown to increase with per cent cover of emergent vegetation (Hargeby et al. 1994; VanRees-Siewert and Dinsmore 1996; Safran et al. 2000; Fairbairn and Dinsmore 2001).

Along the lower Yellow River a range of Anatidae species (e.g. Falcated Duck, Baikal Teal) rely on high levels of productivity in the aquatic vegetation to provide year round food resources, but it is particularly important for those species that overwinter in the region.

8.2.8 Saltmarsh

Saltmarsh is of direct importance to many avian species by providing habitat in which individuals can breed, feed and roost (Saintilan 2009). This vegetation community is an important component of the Yellow River Delta. Saltmarsh shrublands occur around the periphery of relatively saline seasonal and permanent wetlands. Dominant species include *Suaeda salsa*, *Halosarcia* spp. and *Sarcocornia* spp. Saltmarsh vegetation tolerates, but does not require, inundation (Wilson 1999).

Saltmarsh has been documented as important habitat for several shorebird species in Africa, Europe and North America (Spencer et al. 2009).

8.2.9 Aquatic vegetation

Submerged freshwater aquatic vegetation plant communities occur in fresh/brackish wetlands with open water. Typical species include *Potamogeton* spp., *Myriophyllum* spp., *Triglochin* spp., *Crassula* sp. and *Villarsia* sp. This vegetation provides important structural habitat for a variety of food sources and acts directly as a food source for many bird species.

Chara spp. are benthic aquatic alga with a plant-like habit that forms extensive and essentially monocultural beds in some semi-permanent wetlands. This species serves a similar ecological role as freshwater aquatic vegetation in providing habitats for fish and macroinvertebrates, but often survives in saline environments where other plants are absent. An increase in *Chara* spp. biomass in a lake in the Netherlands was strongly correlated with an increase in the abundance of herbivorous waterbirds (Noordhuis et al. 2002), illustrating its likely importance to the productivity of higher trophic levels and in supporting wildlife populations. *Chara* spp. beds may act as nutrient sinks in wetlands (Kufel and Kufel 2002), thus helping to control nutrient concentrations in the water column and maintaining ecosystem stability.

These beds of aquatic vegetation are the basis of a complex food chain, providing forage for waterbirds through a complexity of interactions.

8.3 Terrestrial birds and wetlands

Energy and nutrient flux between wetland and terrestrial food webs is important to the productivity and diversity of both aquatic and terrestrial ecosystems.

During and subsequent to a flood the related increase in primary productivity across a floodplain, and in wetlands, is the basis of a complex terrestrially based food web. Inundated over-storey provides foraging, refuge and breeding habitat for terrestrial fauna species. Following water recession the subsequent growth of understorey provides forage for herbivores again contributing significant productivity to the terrestrially based food web. Many species that forage in the region will move to the area for refuge and breeding. Heterogeneity in lowland floodplain macrohabitat has been shown to significantly increase local avian biodiversity (Parkinson et al. 2002).

In addition to the increased productivity of the floodplain and fringing vegetation subsequent to inundation, there is ultimately an additional faunal-mediated transfer of energy and resources from the aquatic environments to the adjacent terrestrial environments, increasing the productivity of those terrestrial environments (Ballinger and Lake 2006). The emergence of adult insects from the water contributes significantly to riparian consumers such as insectivorous birds (Baxter et al. 2005). Densities and diversity of non-aquatic woodland bird species, for example, have been shown to increase significantly with the presence of wetlands in woodlands when compared with equivalent woodland habitat without wetlands (Parkinson et al. 2002, Ballinger and Lake 2006). This exchange may influence ecosystem productivity at the landscape scale (Ballinger and Lake 2006), contributing to breeding activity and success across a suite of terrestrial faunal species.

The fauna community associated with the lower Yellow River floodplain and riparian zone and wetlands is therefore complex and diverse. A large number of species make use of the area in differing ways, and are reliant upon inundation of the floodplain and wetlands and the presence of healthy floodplain and riparian vegetation as the basis of the community.

Changes to the extent and nature of movement of energy and nutrients from riverine wetlands to the surrounding terrestrial landscape will significantly impact on the productivity of linked terrestrial fauna communities. For example the *Tamarisk* community associated with the Yellow River floodplain and delta provides a nectar source and high seed biomass, which in turn supports an invertebrate community, all of which are important to a range of nectivorous, granivorous and insectivorous terrestrial birds.

8.4 Representative waterbird flow dependent habitat requirements

8.4.1 Swan Goose

The Swan Goose, *Anser cygnoides*, has its key breeding grounds in the border area between Russia, Mongolia and mainland China (BirdLife International 2011). Historically small populations migrated to North Korea and South Korea, but it now winters entirely in eastern China (Cao et al. 2008). Swan geese arrive in eastern China in late October and November, and depart in early March (Cheng et al. 2009). In winter, it occurs in lowland lakeside marshes, rice-fields, estuaries and tidal flats. The birds migrate in stages, stopping at a number of sites en route between breeding and wintering grounds. Present day key wintering sites lie along the coast of Jiangsu and around the lakes of Poyang Hu and Dongting Hu in the Yangtze basin, China. The Swan Goose is recorded at Mengjin Huanghe Nature Reserve, Yubei Huanghe Gudao Nature Reserve, Kaifeng Liuyuankou Nature Reserve (BirdLife International 2009) and the Yellow River Delta (Zhao and Song 1995). The Swan Goose population is estimated at 60,000–80,000 individuals, and has undergone a significant decline in abundance in recent decades (BirdLife International 2010).

Swan Geese forage either by dip-feeding (probing in the substrate in shallow water), grubbing (digging in wet exposed substrate above the waterline), or grazing (feeding on dry terrestrial vegetation) (Zhang Y et al. 2010). They preferentially feed on submerged macrophyte tubers, particularly those of *Vallisneria spiralis*. This food source is typically made successively available from muddy lake sediments by winter water level recession, making the species highly vulnerable to hydrological change in the seasonally flooded wetlands on the Yellow River floodplains. During a study of the bioenergetics of this species in the main wintering areas along the eastern Chinese coast and in the Yangtze River basin, a high proportion of its diet (at both lakes and coastal areas) was found to comprise of the roots of a waterplant, *Vallisneria asiatica*, and the seeds of a halophyte, *Suaeda salsa* (BirdLife International, 2001); this diet was similar to that of many other waterbirds in these areas, especially the wintering Siberian Cranes *Grus leucogeranus* at Poyang Hu (BirdBase 2011a).

Water regime changes may impact on Swan Geese, particularly through lower summer water levels caused by delayed, reduced or shortened summer floods. Low summer water levels can reduce the extent of deep water habitat available to submerged water plants such as *Vallisneria* and *Potamogeton* and promote floating and emergent aquatic plants that are less suitable food sources. Mud flats that are exposed to falling water levels too early in the year may become dry and too hard for birds to be able to dig for and feed on plant tubers. A reduction in these food sources can force Swan Geese to switch to less nutritious diets and to graze in *Carex*/*Phalaris* meadows (Zhang Y et al. 2010).

The Swan Geese are representative of a range of tuber feeding bird species that overwinter in the region, for example the Hooded Crane *Grus monacha*, which have been shown to shift their diet to spilt rice in lakeside paddies when tubers are unavailable (Zhou et al. 2009), tundra swans, *Cygnus columbianus*, and Siberian Crane, *Grus leucogeranus*.

The Swan Geese and other species would benefit from the provision of lake edge habitats of low slope that are exposed during the winter spring period. This provides soft mud for efficient grubbing during the overwintering period.

Recent Swan Goose range contraction and population decline appear to be linked with the historical decrease in submerged plant coverage across floodplains of regulated rivers (Zhang Y et al. 2010).

The key environmental flow requirements of the Swan Goose have linkages to:

- conditions that promote submerged aquatic tuber producing macrophytes e.g. *Vallisneria* and other food plants preceding winter migration period
- gradual drawdown of water levels from summer highs between early October and late December/January
- inundation, and then exposure, of geomorphic features to maximise mudflat availability
- timing and extent of flooding.

8.4.2 Bean Goose

The Bean Goose *Anser fabalis* is strongly migratory and travels between breeding grounds in Russia but overwinters in eastern China. Its preferred habitat is large lakes, marshy wetlands and agricultural lands, but is found on rivers when staging during migration.

In eastern China the Bean Goose is present in small numbers in October and early November, but increases greatly in numbers during November and December, with birds beginning to depart in February and few left at the end of March (Cheng et al. 2009). The Yellow River Delta Nature Reserve is one of the important bird areas (IBA) for Bean Goose (BirdLife International 2011) and it is also found in Mengjin and Zhengzhou Nature Reserves (BirdLife International 2009).

The species is herbivorous, its diet consisting of herbs, grasses, sedges and mosses. In eastern China bean geese forage preferentially in *Carex* meadows, but they also dabble along lake edges and feed on underwater vegetation by head-dipping and upending whilst swimming (Cheng et al. 2009). In Europe during the winter it feeds predominantly on agricultural land taking grain, beans, potatoes and sprouting winter cereal crops. It is important that water levels remain low in March to expose foraging areas. In Anhui Shengjin Lake National Nature Reserve, Cheng et al. (2009) found that unnaturally high water levels in March greatly reduced the available foraging area at a time when birds would normally be fattening in preparation for migration to the breeding grounds.

The key environmental flow requirements of the Bean Goose have linkages to:

- summer flooding conditions that increase *Carex* productivity
- winter low flow levels to expose *Carex* meadows
- avoidance of increased water levels until at least mid-March to retain foraging habitat for birds fattening prior to departing on their northward migration.

8.4.3 Grey Heron

Some populations of the Grey Heron, *Ardea cinerea*, are fully migratory, dispersing widely in September - October after the breeding season and returning to breeding grounds in February. Further south in temperate areas, populations tend to be sedentary or only partially migratory, breeding in spring and summer. The species breeds in mixed colonies of hundreds or thousands of pairs (the largest colony in Europe is 800–1300 pairs), although it may also nest solitarily or in small groups of 2–10 nests (BirdLife International 2011).

The species is typically a solitary feeder but may congregate in large numbers where feeding areas are restricted or temporary food sources are abundant. It feeds at any time day or night, but is most active at dawn or dusk, typically roosting communally or solitarily during the middle of the day and at night in trees.

This species is a generalist in its habitat use, although shallow water, relatively large prey, and four or five months of ice-free breeding season are among the essential characteristics of its habitat. It inhabits any kind of shallow water, fresh, brackish or saline, both standing and flowing, and shows a preference for areas with trees, as it is commonly an arboreal rooster and nester (BirdLife International 2011). Grey Herons forage at lakes, large rivers and shallow coastal lagoons (Brazil 2009). Li et al. (2011) found that the bird species of the buffer and transition zone of the Yellow River Delta Nature Reserve, which experience a relatively high degree of human activity and disturbance, were dominated by species considered to be tolerant of anthropogenic threats on their habitat. One of these was Grey Heron. This bird is resident over most of China (Brazil 2009), so it would also be expected in Mengjin, Zhengzhou, Kaifeng and Yubei Nature Reserves.

The Grey Herons diet consists predominantly of fish and eels 10–25 cm long, as well as amphibians, crabs, molluscs, crustaceans, aquatic insects, snakes, small rodents, small birds and plant matter (although this may be incidental, or only to aid in pellet formation) (BirdLife International 2011).

The nest is a stick platform that is often re-used over successive years, usually positioned high in a tall tree up to 50 m, but also on the ground or on cliff edges, in reed beds or in bushes. In reed-beds nests may be built of reeds, and ground nests may be reduced to a slight scrape, ringed with small stones and debris. The species commonly nests in colonies, and nesting sites are typically situated 2–38 km (convenient flying distance) from preferred feeding areas (BirdLife International 2011).

The key environmental flow requirements of the Grey Heron have linkages to:

- spring–summer inundation of *Phragmites* and *Typha* reed beds as breeding habitat
- large areas of shallow water (<0.3 m) over mud or sand base, with submerged or emergent aquatic plant community
- conditions favouring diverse and abundant small-to-medium fish species.

8.4.4 Hooded Crane

The Hooded Crane *Grus monacha* breeds in south-central and south-eastern Siberia, Russia. Breeding is suspected in Mongolia and two breeding sites have recently been found in the region of Heilongjiang, China (BirdBase, 2011b). Its global population is estimated to be c. 11,500 birds with 1,460 in China and Russia (BirdLife International, 2011). It breeds in remote, wooded, upland bogs on gently sloping foothills and flat river terraces, mostly within the permafrost zone. It winters in freshwater marshes, wet grassland, coastal tidal flats and farmland (BirdLife International, 2011).

The Hooded Cranes are present at migration staging grounds in the Yellow River Delta Nature Reserve in Shandong from mid-October to early November in autumn, and from late March to early April in spring (Zhao and Song 1995).

On migration, and in winter, Hooded Cranes use a wide variety of habitats. In China, they tend to roost along the shores of rivers and shallow lakes, and to forage along the muddy edges of lakes and in nearby grasslands, grassy marshes, rice paddies and agricultural fields (Meine and Archibald 1996). At migratory stopovers in China they occur in three major types of habitat: (i) freshwater marshes (including *Phragmites* reedbed and *Carex* marsh) and wet grasslands, surrounded by grassland, farmland and fishponds (at Zhalong, Melmeg and Xianghai in north-east China); (ii) coastal wetlands, with wide intertidal mudflats, coastal marshland, saltworks, fishponds and prawn ponds, with dominant vegetation including *Phragmites*, *Typha* and *Carex* (at the Gulf of Bohai, Yalu estuary, Beidaihe and Yellow River Delta); (iii) floodplains and lakeshores, and nearby farmland at the Yellow River (Wang Q 1998).

On spring migration, they feed on crops of wheat, corn and buckwheat. Migrants at the Yellow River delta feed mainly on wheat shoots and soybean, and also eat some invertebrates. The wintering birds in the lower Yangtze basin feed mainly on aquatic plants in lakes and on grains in farmland; at Shengjin Hu they feed mainly on the roots of *Vallisneria spiralis*, at Poyang Hu they mainly eat the stems and roots of Cyperus, and rice and wheat grain on farmland (BirdLife International 2011), and at Anhui Shengjin Lake they feed on fallow rice paddies and along the lake edge and in *Carex* meadows (Cheng et al. 2009).

The migratory and wintering habitats of Hooded Cranes are under threat throughout China because of the reclamation and degradation of wetlands linked to rapid economic development (BirdBase 2011b), for example, areas of shallow marshland are being lost at many lakes in the lower Yangtze basin owing to reclamation, the construction of dams and snail control (Wang Q 1998).

The key environmental flow requirements of the Hooded Crane have linkages to:

- exposed mudflats in spring and autumn
- annual cycles of wetland flooding and drying
- maintenance of diverse reed bed plant communities including *Phragmites, Typha* and *Carex*
- summer flooding conditions that increase *Carex* productivity
- winter low-flow levels to expose Carex meadows
- avoiding increased water levels until at least mid-March to retain foraging habitat for birds fattening prior to departing on their northward migration.

8.4.5 Black-crowned Night-Heron

Black-crowned Night-Heron, *Nycticorax nycticorax*, occurs as both a resident in, and a summer migrant to, the Yellow River region. Southward movements occur after breeding from September to October. Return northward movements occur from March to May (Birdlife International 2011).

The species is largely crepuscular and nocturnal, but may feed diurnally especially during the breeding season. It disperses from colonial roosts in trees above water at dusk to feed at wetlands (Brazil 2009). It is an opportunistic feeder taking fish, frogs, tadpoles, turtles, snakes, lizards, adult and larval insects (e.g. beetles, bugs, grasshoppers, crickets, flies and dragonflies), spiders, crustaceans, molluscs, leeches, small rodents, bats and the eggs and chicks of other bird species (Birdlife International, 2011).

Black-crowned Night-Heron inhabits fresh, brackish or saline waters with aquatic vegetation and bamboo or trees (e.g. poplar, pine, oak or mangroves) for roosting and nesting; it shows a preference for islands or predator-free areas for nesting sites (Birdlife International 2011). It occupies the forested margins of shallow rivers, streams, lagoons, pools, ponds, lakes, marshes and mangroves and may feed on pastures, reservoirs, canals, aquaculture ponds and rice-fields. Black-crowned Night-Heron has been found in Zhengzhou wetlands; a location that is thought to be the northern limit of its wintering range (Wang and Zhang 2004). Here it has developed a series of ecological adaptations in the wintering population, including decreased activity in daylight, enhanced habituation, and taking shelter from the wind on the south facing bank of sewage ditches (Wang and Zhang 2004). Black-crowned Night-Heron is also found on the Yellow River Delta (Zhao and Song 1995), and generally on the Yellow River in Henan Province (Henan Province Forestry Hall 2001). This bird is virtually cosmopolitan in China (Brazil, 2009), so it was assumed to also occur in Kaifeng, Mengjin and Yubei Nature Reserves.

The nest is a platform constructed of sticks and vegetation placed 2–50 m above water or on dry ground near water in trees, bushes, and reedbeds.

The key environmental flow requirements of the Black-crowned Night-Heron have linkages to:

- annual cycles in water levels to maintain an extensive and diverse fringing and riparian habitat
- healthy and diverse aquatic ecosystem.

8.4.6 Spotted Redshank

The Spotted Redshank *Tringa erythropus* is a full migrant, breeding in the subarctic and arctic zone. On passage to its wintering grounds the majority of the species travels overland on a broad front, although there is also an important route down the east coast of China where the species is found in intertidal areas and adjacent non-tidal wetlands. Numbers are probably underestimated, as this species often occurs on non-tidal wetlands, which are generally less well surveyed than intertidal areas (BirdLife International 2011). The Yellow Sea is important for this species during northward migration, when it supports about 50 per cent of the estimated flyway population. Large numbers also occur on southward migration and the species is common in eastern China during the non-breeding season. Large numbers were recorded in November and December inland in China around the Anhui Shengjin Lake on the Yangtze River (Cheng et al. 2009). The Spotted Redshank was observed by Li et al. (2011) in the Yellow River Delta Nature Reserve. This bird is virtually cosmopolitan in China (Brazil 2009), so it was assumed to also occur in Kaifeng, Mengjin, Zhengzhou and Yubei Nature Reserves.

During migration, and on its wintering grounds, this species frequents a variety of freshwater and brackish wetlands such as sewage farms, irrigated rice fields, brackish lagoons, salt-marshes, salt-pans, sheltered muddy coastal shores and mudflats, marshes and marshy lake edges, small reservoirs, pools and flooded grasslands (BirdLife International 2011).

Spotted redshank is carnivorous, with its diet consisting chiefly of aquatic insects and their larvae (especially swimming beetles and hemipterans), terrestrial flying insects (such as craneflies), small crustaceans, molluscs, polycheate worms, and small fish and amphibians up to 6–7 cm long (BirdLife International 2011).

The Spotted Redshank is threatened by habitat loss in its wintering range and on migration. In China and South Korea important migrational staging areas around the coast of the Yellow Sea are being lost through land reclamation and degraded as a result of declining river flows (from water abstraction), increased pollution, unsustainable harvesting of benthic fauna and a reduction in the amount of sediment being carried into the area by the Yellow and Yangtze Rivers (BirdLife International 2011).

The key environmental flow requirements of the Spotted Redshank have linkages to:

- annual pre-regulation cycles of inundation and exposure of wetlands and resultant high levels of productivity
- receding water levels and exposure of extensive mudflat regions during autumn in association with southward migration, and in spring during northward migration
- timing and extent of annual sediment flow into the delta, with the historically high levels of sediment load preferred.

8.4.7 Baer's Pochard

Baer's Pochard, *Aythya baeri*, is a deep-water diving duck. It is internationally endangered with populations of 5,000 birds and believed to be declining through loss of wetland habitat (Birdlife International 2011).

Baer's Pochard is a winter and transient migrant that breeds in the Amur and Ussuri basins in Russia and north-eastern China (Birdlife International, 2011). It winters mainly in eastern and southern mainland China (c. 850 individuals), India, Bangladesh (1000–2000 individuals) and Myanmar (1000–1500 individuals). In China, pairs begin to form from mid-April and egg-laying begins from mid- to late-May, with the latest record of a clutch being 28 June (BirdLife International 2011).

It inhabits small lakes, larger shallow lakes, as well as fast-flowing rivers and streams, providing there is rich aquatic vegetation. It breeds around lakes with rich aquatic vegetation in dense grass or flooded tussock/shrubby meadows. In Liaoning, China, it is usually found in coastal wetlands with dense vegetation, or on rivers and ponds surrounded by forest. In winter, it occurs on freshwater lakes and reservoirs. During migration, Baer's pochard will stop to rest on reservoirs, lakes and rivers. In the winter it selects wetlands such as marshes, paddy fields, and sandy islands within freshwater lakes (Brazil 2009; Birdlife International 2011). Baer's Pochard is found in Mengjin, Yubei, Kaifeng, and Zhengzhou Nature Reserves, the Yellow River generally in Henan Province (Henan Province Forestry Hall 2001), and the Yellow River Delta (Zhao and Song 1995).

Baer's Pochard feeds almost entirely by diving. It can dive and remain submerged for around 40 seconds, reaching a depth of about two metres. It is omnivorous, and during the migration seasons it feeds mainly on aquatic plants and seeds, but it takes more animal food (insects, molluscs, shrimps and fish) during the breeding season (BirdLife International 2011).

The key environmental flow requirements of the Baer's Pochard have linkages to:

- conditions that promote submerged aquatic plant growth preceding winter migration period
- large areas of ice free lakes, reservoirs and main river channel in winter.

8.4.8 Saunders's Gull

Saunders's Gull *Saundersilarus (*Previously *Larus) saundersi* is an internationally vulnerable species. Saunders's Gull appears to be almost exclusively coastal in distribution, with very few inland records (Birdlife International 2011; BirdBase 2011c). It breeds in eastern mainland China, where the Yellow River delta is one of only three known sites. The most important breeding grounds are Yancheng and Shuantai Hekou in China. It winters in eastern and southern China, from Jiangsu southwards, with the key wintering grounds in Bohai Bay (where 866 birds were counted in 2005/2006). The global population is estimated to be 7100–9600 birds and appears to be declining (BirdLife International 2011).

Saunders's Gull nests on the ground in *Suaeda*-dominated saltmarsh, an extensive plant community in the Yellow River delta (Birdlife International 2011). It nests in the pioneer level of saltmarsh, in a belt from around the high tide mark extending seaward up to 1000 m, where the rapid rate of accretion results in a band of consolidated but largely bare mud or sand at the seaward side of the saltmarsh with scattered plants of woody *Suaeda* and *Aeluropus littoralis* grass (BirdLife International 2011).

Wintering birds are found on estuarine tidal (mud and sand) flats with regular movements between different sites dependent on weather and food supply (Birdlife International 2011).

This species primarily feeds on exposed intertidal mudflats (BirdLife International 2001). In the Yellow River Delta, birds especially favour the mouth of the river (BirdBase 2011c). They also use drained fishponds. The species has a distinctive, specialised feeding behaviour, flying with rather stiff, tern-like wing-beats over a mudflat at a height of about 10 m (sometimes lower, occasionally up to 30 m), and on sighting prey on the mud surface diving vertically and, on landing, immediately pecking at the prey item; this behaviour appears to be adapted to hunting crabs and mudskippers, which react very quickly to movement by entering burrows in the mud (BirdLife International 2001).

Reclamation and economic development of tidal flats is also the main threat to Saunders's Gull in mainland China (BirdBase 2011c). Most of the natural coastal saltmarshes of China have already been reclaimed, and the remaining natural coastal habitats are being replaced by aquacultures, especially shrimp-ponds (BirdBase 2011c). Human activity is high around the Gulf of Bohai, and there has already been encroachment into many areas of mudflats for farmland, saltworks or shrimp-ponds (BirdBase, 2011c). The southern side of the Yellow River estuary in Shandong consists of a very large wetland area with numerous channels and little human activity, but much of the northern side of the estuary has been reclaimed for shrimp-ponds, saltpans and oilfield activities (BirdBase 2011c). On the Yellow River delta, Saunders's Gull is under increasing threats from pollution and human activities.

The key environmental flow requirements of the Saunders's Gull have linkages to:

- hydraulic and geomorphic features related to ongoing growth of the river delta and health of the associated estuarine tidal mudflats
- ongoing succession of vegetation types on the Yellow River delta
- maintenance of healthy *Suaeda* saltmarsh habitat.

8.4.9 Dalmatian Pelican

The eastern race of the Dalmatian Pelican Pelecanus crispus is migratory in Asia, breeding in western Mongolia in summer and migrating to southeast China for the winter. In September and October the birds appear to migrate from Mongolia south-eastward, down the Yellow River to the Bohai Sea and then along the Yellow and East China Sea coasts towards the main modern day wintering areas in southeast China (Shi et al. 2008). Return migrations to the breeding grounds follow the same general path in April and May. The pelicans are believed to migrate using wetland stopover sites for a day or two, but staying at a fewer sites for longer periods. Historically the population wintered (December to March) along the Yellow Sea coast and the Yangtze, Huai and Yellow River floodplains, but the current wintering area is predominately south-eastern China, although birds use the Henan Yellow River Wetland National Nature Reserve (which includes Mengjin Huanghe Nature Reserve) (Shi et al. 2008). It is estimated the population is presently only 50 birds. Li et al. (2011) reported this species present at the Yellow River Delta Nature Reserve.

The diet of the Dalmatian Pelican consists almost entirely of fish, especially carp *Cyprinus carpio*, perch *Perca fluviatilis*, rudd *Scardinius erythrophthalmus*, roach *Rutilus rutilus*, and pike *Esox lucius* in freshwater wetlands, and eels, mullet, gobies and shrimps in brackish waters. Reduction in fish biomass through overfishing and changes in river flows are postulated to be impacting on the species feeding ecology (Shi et al. 2008).

A major threat to the species is habitat loss (BirdLife International 2001).

The key environmental flow requirements of the Dalmatian Pelican have linkages to:

- diverse and abundant fish species along main channel, in lateral wetlands and in the delta and estuary
- hydraulic and geomorphic features related to ongoing growth of the river delta and health of the associated estuarine tidal mudflats.

8.4.10 Sand Martin

The Sand Martin (or Bank Swallow), *Riparia riparia*, is a migrant to northern China and Russia where it breeds during summer. Sand Martins are found almost exclusively near water, along rivers, at lakes and wetlands. Their food consists of small insects, mostly gnats and other flies whose early stages are aquatic.

Birds nest in vertical soil banks and cliffs with no trees or shrubs in front, which are abandoned after two to three years in favour of new banks with less compact soils (Heneberg 2009). Sand martin excavate almost exclusively in actively eroding banks and bluffs, requiring an almost sheer embankment for burrowing, to avoid predators, such as snakes and foxes (Girvetz 2010). Thus, the most important role water plays may be the creation and maintenance of suitable natural nesting habitat. Water that flows or is moved by waves is important to maintain natural nesting habitat (Garrison 1989). The installation of rock bank revetment blocks access to the sheer embankments where Sand Martins nest and stops the process of river-bank erosion that maintains these embankments. Girvetz (2010) found that on the Sacramento River, US, the removal of bank erosion control (bank revetment) projects would increase viability of this population.

Sand Martins generally live along the Yellow River in Henan Province (Henan Province Forestry Hall 2001), in the Yellow River Delta (Zhao and Song 1995), and because it is widespread across eastern China (Brazil 2009) it would be expected in Mengjin, Zhengzhou, Kaifeng and Yubei Nature Reserves.

The key environmental flow requirements of the sand martin have linkages to:

- hydraulic and geomorphic features related to ongoing maintenance of vertical soil banks along the river edge
- high floodplain and wetland productivity through annual flooding and cycles of wetting and drying.

8.4.11 Long-toed Stint

The Long-toed Stint *Calidris subminuta* is strongly migratory and travels largely overland, crossing the Yellow River region: northward in spring and southward in autumn between its breeding and wintering grounds (BirdLife International 2011). The departure from the northern breeding grounds starts in July and peaks between August and September, with the return northward migration peaking between April and May (BirdLife International 2011).

Outside of the breeding season the species occupies shallow inland wetlands and although it shows no preference over fresh, brackish or saline waters it does require habitats with soft, muddy shorelines and short grass sedges, floating aquatic vegetation, reeds and rushes (BirdLife International 2011). Suitable habitats include the edges of permanent and temporary lakes, ponds, reservoirs, lagoons, swamps, and streams, river flood-plains, marshes, rice-fields, sewage ponds, saltpans and saltmarshes. The species also less frequently occurs around tidal estuaries on intertidal mudflats (BirdLife International 2011). The Long-toed Stint occurs generally along the Yellow River in Henan Province (Henan Province Forestry Hall, 2001), so would be expected in Mengjin, Zhengzhou, Kaifeng and Yubei Nature Reserves. It may occur on the delta, but is not likely to be present in high numbers there.

Its diet includes insects (e.g. carabid beetles), small gastropod molluscs, crustaceans amphibians and seeds.

The key environmental flow requirements of the long-toed stint have linkages to annual cycles of wetland flooding and drying.

8.4.12 Common Kingfisher

The Common Kingfisher *Alcedo atthis* is a resident species in eastern China and migratory to northern China and Russia. Its habitat includes a wide range of wetlands, lakes and ponds, wooded streams and rivers, where flow nil or very slow. They typically plunge dive for small fish, either from a secluded perch or hovering flight. The feed on small-bodied fish and shrimp (3–5 cm in length) (Helbig 2005). Common Kingfisher nest preferentially in holes they dig by themselves in vertical soil banks (Heneberg 2009).

The Common Kingfisher occurs generally along the Yellow River in Henan Province (Henan Province Forestry Hall 2001), in the Yellow River delta (Zhao and Song 1995), and because it is widespread across north-eastern China (Brazil 2009) it would be expected in Mengjin, Zhengzhou, Kaifeng and Yubei Nature Reserves.

The key environmental flow requirements of the common kingfisher have linkages to:

- hydraulic and geomorphic features related to ongoing maintenance of vertical soil banks along the river edge
- flooding and maintenance of backwaters and wetlands on floodplains
- healthy and diverse small-bodied fish and shrimp populations in wetlands.

8.4.13 Red-crowned Crane

Red-crowned Crane *Grus japonensis* breeds in south-eastern Russia, north-east China, Mongolia (first record in 2001) and eastern Hokkaido, Japan. The Russian and Chinese populations mainly winter in the Yellow River delta (Li et al. 2011) and the coast of Jiangsu province, China, and the Demilitarised Zone, North Korea/South Korea (Birdlife International 2011). Staging areas exist along the Yellow River between the provinces of Shanxi and Shaanxi. The Japanese population is non-migratory. The world population is estimated at c. 2750 birds, although since it has a long generation length (12 years), this figure is likely to include only 1650 mature individuals (Birdlife International 2011). The wintering population in China totals c. 1000 birds at two sites and is declining (Birdlife International 2011).

The Red-crowned Crane is classified internationally as Endangered because it has a very small population, and although the population in Japan is stable, the mainland Asian population continues to decline owing to loss and degradation of wetlands through conversion to agriculture and industrial development (Birdlife International 2011). This species is highly sensitive to human disturbance activities.

The habitat suitability of the Red-crowned Crane in the Yellow River Delta Nature Reserve, for the years 1992, 1999 and 2006, was determined by Cao and Liu (2008) using an Ecological Niche Suitability Model (ENSM). The Red-crowned Crane is a wetland species being accustomed to the habitat of marsh, tidal flat with sparse vegetation and little disturbances (Birdlife International 2011). Using previous research by other authors, Cao and Liu (2008) tabulated the habitat requirements of the Red-crowned Crane (Table 28). Reed wetland with *Suaeda* is the first choice for the Red-crowned Crane, whether it is in breeding, migration or wintering period (Fu et al. 2009).

There is high adult mortality in Red-crowned Crane in some mainland China wintering areas, which is apparently due to poisoning; the species has been found to carry high levels of heavy metal contamination (BirdLife International 2011).

The Red-crowned Crane eats small amphibians, aquatic invertebrates, insects, and plants that grow in marshes and swamps (BirdLife International 2011).

The key environmental flow requirements of the red-crowned crane have linkages to:

- spring/summer inundation of *Phragmites* and *Typha* reed beds and *Suaeda* as breeding habitat, with *Tamarisk* being unsuitable
- large areas of shallow water (< 0.3 m) over mud or sand base, with submerged or emergent aquatic plant community, distant from human activities and structures
- year-round baseflows, plus flushing flows to remove dissolved metal and metalloid contaminants.

Table 28. Habitat suitability factors for the Red-crowned Crane.

Habitat factors		Suitable habitat	Moderately suitable habitat	Unsuitable habitat
Vegetation type		**Reed marsh,** ***Suaeda***	**Salt pan, fishponds, reed meadow, bare tide flat**	**Forest,** ***Tamarisk*** **shrubland, farmland, large deep water body**
Water resource	Distance to shallow water	0 – 500 m	500 – 1,000 m	>1,000 m
	Distance to tide ditch	0 – 500 m	500 – 1,000 m	>1,000 m
Human disturbances	Distance to road	>500 m	200 – 500 m	<200 m
	Distance to oil well	>500 m	300 – 500 m	<300 m
	Distance to urban area	>500 m	300 – 500 m	<300 m

Adapted from Cao and Liu (2008).

8.5 Waterbird flow objectives

The environmental flow requirements determined for all key flow dependent species were compiled, and associated with reaches/assets (based on where the species have been observed). The objectives were then expressed as flow-ecology-species-asset relationships (Table 29). The assets 'Yubei Huanghe Gudao Nature Reserve' and 'Dongping Hu' were not included here because their hydrological regimes are largely disconnected from that of the lower Yellow River. The asset 'Intertidal zone around the Yellow River Estuary and the Bohai' was considered part of the delta asset. It is apparent from the compiled objectives (Table 29) that all flow components (Table 16) are important in all reaches for the maintenance of diverse and abundant waterbird populations in the lower Yellow River. Although flow pulses would likely provide some benefit to waterbirds, the available knowledge did not indicate that pulses were critical for waterbirds. The full suite of waterbird flow-ecology objectives was simplified to a list of key objectives and flow requirements for waterbirds (Table 30).

Table 29. Waterbird flow-ecology-species-asset relationships.

Flow component	Timing	Ecological objective	Species	Reach number and asset				
				1, 2, 3, 4 Channel	1 Mengjin	1 Zhengzhou	1 Kaifeng	4 Delta
Low flows to expose low slope mudflats	Nov to mid-Mar	Avoidance of increased water levels until at least mid-March to retain Carex foraging habitat for birds fattening prior to departing on their northward migration.	bean goose *Anser fabalis*		X	X		X
			hooded crane *Grus monacha*			X	X	X
	early-Oct to Feb	Large areas of shallow water (<0.3 m) over mud or sand base, with submerged or emergent aquatic plant community	grey heron *Ardea cinerea*	X	X	X	X	X
	early-Oct to Jan	Inundation, and then exposure, of geomorphic features to maximise mudflat availability	swan goose *Anser cygnoides*		X		X	X
	by Oct	Winter low flow levels to expose Carex meadows	bean goose *Anser fabalis*		X	X		X
			hooded crane *Grus monacha*			X	X	X
	Mar-Jun; Sep-Nov	Exposed mudflats in spring and autumn	hooded crane *Grus monacha*			X	X	X
	Mar-Jun; Sep-Nov	Receding water levels and exposure of extensive mudflat regions during autumn in association with southward migration, and in spring during northward migration	spotted redshank *Tringa erythropus*	X	X	X	X	X
	early-Oct to Feb	Large areas of shallow water (< 0.3 m) over mud or sand base, with submerged or emergent aquatic plant community, distant from human activities and structures	red-crowned crane *Grus japonensis*			X	X	X
Low flows and low flow pulses to minimise ice formation	Dec-Feb	Large areas of ice free lakes, reservoirs and main river channel in winter	Baer's pochard *Aythya baeri*	X	X	X	X	X

Flow component	Timing	Ecological objective	Species	Reach number and asset				
				1, 2, 3, 4 Channel	1 Mengjin	1 Zhengzhou	1 Kaifeng	4 Delta
High flow extended flow recession to prevent mudfats from drying	early-Oct to Jan	Timing and extent of flooding	swan goose *Anser cygnoides*		X		X	X
	early-Oct to Jan	Gradual drawdown of water levels from summer highs between early October and late December/January	swan goose *Anser cygnoides*		X		X	X
High flows for growth of submerged macrophytes	Jul-Oct	Conditions that promote submerged aquatic plant growth preceding winter migration period	Baer's pochard *Aythya baeri*	X	X	X	X	X
		Conditions that promote submerged aquatic tuber producing macrophytes e.g. Vallisneria and other food plants preceding winter migration period	swan goose *Anser cygnoides*		X		X	X
		Maintenance of diverse reed bed plant communities including Phragmites, Typha and Carex	hooded crane *Grus monacha*			X	X	X
Low flows, high flow and high flow pulses to generate wetland wet and dry cycle	Natural seasonality	Annual cycles of wetland flooding and drying	hooded crane *Grus monacha*			X	X	X
		Annual pre-regulation cycles of inundation and exposure of wetlands and resultant high levels of productivity	spotted redshank *Tringa erythropus*	X	X	X	X	X
		High floodplain and wetland productivity through annual flooding and cycles of wetting and drying	sand martin *Riparia riparia*	X	X	X	X	X
		Annual cycles of wetland flooding and drying	long-toed stint *Calidris subminuta*	X	X	X	X	X
High flows, low flows, and bankfull flow	Natural seasonality	Year round baseflows, plus flushing flows to remove dissolved metal and metalloid contaminants	red-crowned crane *Grus japonensis*			X	X	X
High flow pulse and high flows that increase macrophyte productivity	Aug-Oct	Summer flooding conditions that increase Carex productivity	bean goose *Anser fabalis*		X	X		X
			hooded crane *Grus monacha*			X	X	X
		Spring/summer inundation of Phragmites and Typha reed beds as breeding habitat	grey heron *Ardea cinerea*	X	X	X	X	X
		Spring/summer inundation of Phragmites and Typha reed beds and Sueda as breeding habitat, with Tamarisk being unsuitable	red-crowned crane *Grus japonensis*			X	X	X

Flow component	Timing	Ecological objective	Species	Reach number and asset				
				1, 2, 3, 4 Channel	1 Mengjin	1 Zhengzhou	1 Kaifeng	4 Delta
High flows and bankfull flows to maintain delta progression with adequate riverine sediment supply	Jun-Nov	Timing and extent of annual sediment flow into the delta, with the historically high levels of sediment load preferred	spotted redshank *Tringa erythropus*	X	X	X	X	X
		Hydraulic and geomorphic features related to ongoing growth of the river delta and health of the associated estuarine tidal mudflats	Saunders's gull *Saundersilarus saundersi*					X
			Dalmatian pelican *Pelecanus crispus*					X
		Ongoing succession of vegetation types on the Yellow River delta	Saunders's gull *Saundersilarus saundersi*					X
Bankfull flow	Jul-Oct	Flooding and maintenance of backwaters and wetlands on floodplains	common kingfisher *Alcedo atthis*	X	X	X	X	X
Bankfull flow, and minimise rock beaching	Jul-Oct	Hydraulic and geomorphic features related to ongoing maintenance of vertical soil banks along the river edge	sand martin *Riparia riparia*	X	X	X	X	X
			common kingfisher *Alcedo atthis*	X	X	X	X	X
All flow components to promote healthy aquatic ecosystem	Natural seasonality	Healthy and diverse aquatic ecosystem	black-crowned night-heron *Nycticorax nycticorax*	X	X	X	X	X
		Annual cycles in water levels to maintain an extensive and diverse fringing and riparian habitat	black-crowned night-heron *Nycticorax nycticorax*	X	X	X	X	X
		Maintenance of healthy Suaeda saltmarsh habitat	Saunders's gull *Saundersilarus saundersi*					X
		Conditions favouring diverse and abundant small to medium fish species	grey heron *Ardea cinerea*	X	X	X	X	X
		Diverse and abundant fish species along main channel, in lateral wetlands and in the delta and estuary	Dalmatian pelican *Pelecanus crispus*		X	X		X
		Healthy and diverse small-bodied fish and shrimp populations in wetlands	common kingfisher *Alcedo atthis*	X	X	X	X	X

Table 30. Waterbird-based objectives and flow requirements.

No.	Objective	Flow component	Hydrologic/hydraulic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing	Reach
B1	Foraging	Low flows	Expose *Carex*	Continuous	≥ 75% of the time	Nov–mid-Mar	Reaches 1 and 4
B2	Foraging	Low flows	Shallow water (<0.3 m) over submerged or emergent aquatic plant community with mud or sand base	Continuous	≥ 75% of the time	early-Oct –Feb	Reaches 1 and 4
B3	Foraging	Low flows	Expose mudflats	Continuous	≥ 75% of the time	Mar–Jun; Nov–Jan	Reaches 1 and 4
B4	Wintering area	Low flows	Maintain ice free water bodies*	Continuous	≥ 75% of the time	Dec–Feb	All reaches
B5	Food supply and breeding	High flows	Inundate areas of submerged macrophytes (*Vallisneria*, *Phragmites*, *Typha*, *Carex*, *Tamarisk*)	Continuous	≥ 75% of the time	Jul–Oct	All reaches
B6	Foraging	High-flow recession	Gradually receding water levels from Bankfull peak	Continuous	≥ 75% of the time	Sep–Nov	All reaches
B7	Mudflat foraging habitat creation	Bankfull	An annual event that supplies enough sediment load to at least maintain delta area	≥ 1 per year / ~10 – 30 days duration	≥ 4 in 5 years	Jul–Oct	Reach 4
B8	Summer–autumn habitat area	Bankfull	An annual event to inundate backwaters and wetlands	≥ 1 per year / ≥ ~5 days duration	≥ 4 in 5 years	Jul–Oct	All reaches

* The lower Yellow River is naturally prone to freezing over in the lower reaches in winter. Freezing is routinely managed by YRCC to prevent ice-flood, so this is considered a passive objective that does not require active implementation.

Note: These objectives are the key requirements, simplified from the full suite of flow–waterbird relationships.

Chapter 9. Fish

9.1 Introduction

China's substantial fish biodiversity (estimated to comprise approximately 900 species) has undergone declines in abundance and richness over the last few decades. Currently, 92 fish species are considered endangered, representing about 10% of the total number of fish species in China (He and Chen undated). The key factors influencing the sustainability of China's fish and fisheries resources include (e.g. Lui and Lui 2009; Liu and Pedroli 2006):

- infrastructure associated with hydro-power generation or water resource development
- over-exploitation of fisheries
- pollution of water
- introduced species.

Infrastructure associated with the production of hydroelectric power, or the redistribution of water resources, have had a major influence on the abundance, distribution and diversity of China's fish assemblages (Fu et al. 2003). Dams restrict fish movements critical for habitat selection, foraging, spawning and recruitment. Flow regulation fundamentally changes downstream habitats, either through temporal and spatial changes in the availability of suitable aquatic habitats, or indirectly, through changes in physical habitat attributes including, the substratum and morphology of the river channel, availability of deep and shallow water habitats, backwater and river associated wetland habitats. Dikes and levees are also widely used, particularly in the lower reaches of many rivers in China, to reduce the risks associated with flooding. These structures isolate all but those wetlands that occur on the inner-floodplain, very close to the river channel. Isolation of flood plain wetlands from the river channel represents a significant threat to some potadromous species that undertake short migrations between the two habitats for spawning and recruitment (He and Chen undated).

Decline in fish populations in the Yellow River and its tributaries (e.g. the Yi River – a once important spawning site for Yellow River carp) has been attributed to hydrological changes that have occurred since construction of major reservoirs in the early 1970s (e.g. Cui et al. 2009; Fan and Huang 2004). The main disturbance mechanism identified by the Scientific Panel for this project was the disruption of spawning of many species and/or the loss of habitat continuity (both longitudinal, and lateral to wetlands, which are important for both spawning and recruitment migrations). Similar effects have been documented for the Yangtze River, where significant reductions in fish stocks have been attributed to loss of continuity between riverine and associated wetland habitats (Xie and Chen 1999; Liu and Wang 2010). Hydrological regulation has also impacted significantly on the delta habitats and estuarine fish stocks. Intrusion of seawater, simplification of delta habitats (e.g. the loss of complex tidal creeks) and reduction in nutrient supply to the estuary and near-shore habitats are commonly cited as the key flow related disturbances impacting on fish in the lower reaches of the Yellow River and estuary (e.g. Shu and Fei 2008; Cui et al. 2009; Fan and Huang 2004).

Cease to flow events were not know to have occurred naturally in the lower reaches of the Yellow River. Since water resources development began in earnest in the 1970s (Figure 31, Figure 33, and Figure 36), cease to flow conditions increased in frequency and duration, occurring in all seasons including the winter high flow period (Figure 43 and Figure 44). During the 1970s, 1980s and 1990s, cease to flow conditions frequently occurred between February and July (Figure 43). Many of the fish species spawn between April and August with peak spawning activity occurring in the May–July period. Natural seasonal changes in hydrology, including increases in water temperature and flow during the spring months are thought to have represented important spawning cues in the lower Yellow River (sensu Xichang et al. 2010; Jiang et al. 2010). Jiao et al. (1998) reported a decline in fish diversity in the sea area immediately offshore of the Yellow River estuary in association with extended cease to flow events in the 1980s and 1990s.

9.2 Life history strategies of fish in the Yellow River and associated wetlands and estuary

Approximately 150 species of fish have been recorded from estuarine and freshwater habitats of the Yellow River. In 2007, a widely reported announcement by the Ministry of Agriculture (MoA) stated that approximately a third of these species no longer occur in the catchment, primarily because of the substantial flow and associated habitat modification resulting from the construction of multiple large dams since the 1970s; in the same announcement, MoA estimated that the fish catch in the Yellow River had declined by 40 per cent[25] (e.g. Handwerk 2007). The sustainability of fish populations is considered a priority in terms of flow management, as well as environmental management and restoration more generally (Lui and Lui 2009).

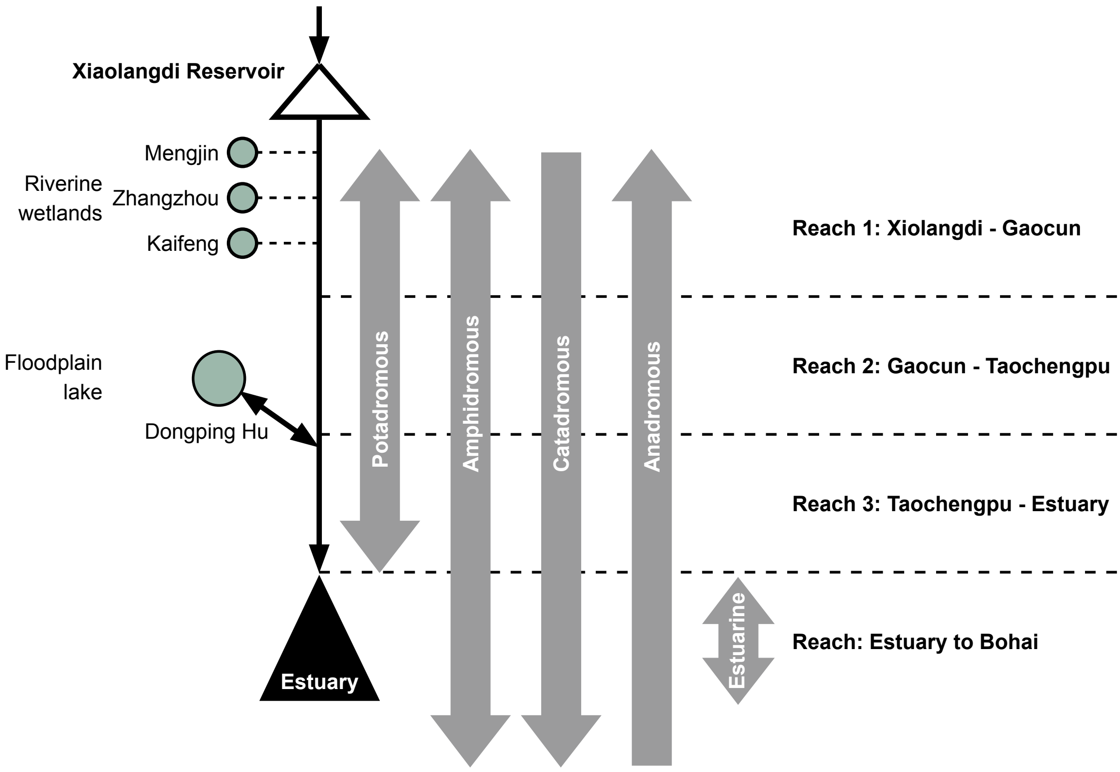
Consideration of the environmental flow requirements of fish requires an understanding of how different species of fish use the variety of habitats that are available to them. This concept extends to an understanding of why fish use particular habitats (e.g. foraging, spawning, growth) and also when fish require access to critical habitats.

25 The reporting does not indicate whether the 40 per cent decline is for freshwater, estuarine or marine fish catch (or all), nor does it indicate the period over which the decline was observed.

Fish use of the Yellow River can be broadly categorised based on their life history strategies, and particularly their requirements for large-scale movements. Fish can be grouped in one of five broad strategies (Figure 82):

1. non-migratory freshwater dependant
2. non-migratory estuarine dependant
3. potamodromous – freshwater migrations
4. anadromous – adults migrate from marine to freshwater habitats for spawning
5. catadromous – adults migrate downstream to marine habitats for spawning.

Figure 82. Life history strategies and use of riverine (freshwater) and estuarine habitats in the lower Yellow River.



Non-migratory freshwater and estuarine dependant species are permanent freshwater or estuarine residents. While they will undertake home range movements in search of food and habitat, there is no requirement for long-distance spawning or recruitment migrations. Consideration of the environmental flow requirements of this group should focus on relationships between flow and the availability of suitable habitats, food and spawning conditions.

Potadromous species undertake movements, within freshwater habitats, for the purposes of spawning or recruitment. In the case of the lower Yellow River, these movements can occur within (upstream and downstream) the main river channel, or between the main river channel and river-associated wetlands. Consideration of the environmental flow requirements for this group should include identification of flow-related migration cues, longitudinal (upstream–downstream) and lateral (river–wetland) habitat connectivity to provide access to spawning sites, as well has the relationships between flow, habitat, food etc. described above.

Anadromous species migrate upstream from marine habitats to spawn in freshwater habitats. Spawning sites may be located either in the main channel or in river associated wetlands such as Dongping Hu, Mengjin, Zhengzhou or Kaifeng Nature Reserves.

Catadromous species migrate downstream from freshwater habitats to spawn at sea. These species are dependant on both freshwater habitats, and to a lesser extent, on the estuarine and/or near-shore environment in order to complete their lifecycle. In additional to the environmental flow requirements already identified (above), relationships between freshwater discharge and tidal exchange and their influence on longitudinal salinity gradients are also important.

9.3 Important features of the lower Yellow River for fish

9.3.1 Reach 1: Xiaolangdi Dam to Gaocun – River channel and associated wetlands

The river, including its immediate floodplain, in this reach comprises a morphologically dynamic channel and the occurrence of backwaters and river associated wetlands that are created and re-shaped during high flow events. Topographic relief within the channel is minor with the majority of the floodplain lying within 2 m of the winter low-flow water level.

These habitats previously represented important spawning habitats for a range of fish species, including the Yellow River carp, when they became inundated by elevated spring flows. Important features of these habitats included areas of low water velocity, and abundant submerged and or emergent vegetation, which is critical for the deposition of eggs and the subsequent survival of new recruits. If they remain connected to the river channel these wetlands support a variety of fish species and represent important seasonal spawning sites for others. Other large lowland rivers in China, such as the Yangtze River, historically had similar reaches that once comprised a complex lacustrine–riverine network (Fu et al. 2003). The importance of wetland and river connection for sustaining fish species has been demonstrated in the Yangtze River, which has experienced rapid declines in fish stocks since the establishment of regulating structures that have stopped the movement of fish between the two habitats. This is especially true for some of the migratory species that spawn in these habitats (Xie and Chen 1999). Liu and Wang (2010) estimated that river-lake disconnection reduced fish diversity of Yangtze River lakes by 38.1 per cent.

9.3.2 Reaches 2 and 3: Gaocun to estuary – River channel and Dongping Hu

The river channel between Gaocun and the estuary is constrained within a complex dike system, and connection between the river channel and floodplain wetlands has been largely lost. The importance of riverine and lacustrine networks for fish spawning, recruitment and habitat has been identified above (Fu et al. 2003). These areas provide shallow, low velocity habitats with abundant submerged or emergent vegetation suitable for spawning and development of early life history stages. However, as described in the geomorphology section of this report, the channelised section (reaches 2 and 3) between Gaucon and the estuary supports very little aquatic vegetation and has simplified physical habitat, with no major wetlands (BirdLife International, 2009). While little information on fish assemblages within this reach of the Yellow River was available for review, the observations of Xie and Chen (1999) and Liu and Wang (2010) of reductions in fish diversity in the Yangtze River following river-lake disconnection suggest that this reach of the Yellow River is likely to currently support a reduced fish diversity. Potadromous species that require access to wetland habitats for spawning and/or recruitment are likely to be especially affected.

In relation to fish communities, Dongping Hu (located near Xiaoqinghe in Shandong Province) represents a critical ecological asset within reach 3. Large lowland rivers in China typically have associated floodplain lakes, fed by tributaries, of which Dongping Hu is an example. Previously these lakes were well connected to the main river, but structures have now isolated most of them (Liu and Wang, 2010). Although the lake's water regime is now strongly regulated (Sun et al. 2007) and connection to the Yellow River is restricted by regulating sluice gates, it provides some indication of the wetland systems that would have occurred naturally. Submerged and emergent vegetation represents an important feature of lacustrine habitats for fish by providing habitat (shelter), spawning substrate (e.g. egg deposition) and food (both herbivorous species, and insectivores that prey on invertebrates within macrophyte beds). Dongping Hu contains open water habitats (where water is too deep to support submerged aquatic macrophyte growth), extensive beds of submerged and semi-emergent macrophytes (e.g. *Hydrilla* sp., *Ceratophyllum* sp., *Myriophyllum* spp., *Potamogeton* spp. and *Vallisneria spiralis*) and emergent reed beds (*Phragmites australis*) (see vegetation section of this report for details).

Dongping Hu provides complex habitats that support a variety of resident fish species. When previously connected with the main river the lake also supported important populations of migratory fish such as saury (*Coilia ectenes*) that migrated upstream to spawn in these habitats (Cai et al. 1980). Connectivity between Dongping Hu and the Yellow River was compromised when sluice gates were constructed on the entrance to the river, and also due to cease-to-flow conditions that occurred in the main river from the 1970s until 1999 (Figure 44). This reduced connectivity led to significant reductions in fish abundance (Jiang et al. 2009). Bo Hu, located in the lower reaches of the Yangtze River, is a similar example of the impact of reduced connectivity on migratory fish. Here, migratory fish abundance decreased from 56 per cent of the total catch before the building of sluice gates in 1956 to 20% of the total catch after the building of sluice gates (Zeng 1990).

9.3.3 Reach 4: Estuary

Estuaries and near-shore marine zones are often highly productive areas that support a variety of unique biota. These conditions are maintained by the mixing of riverine and marine waters, in usually sheltered and shallow habitats that provide suitable conditions for highly productive ecosystems. Historically, the Yellow River discharged massive quantities of sediments (Shu and Fei 2008) and nutrients (Liu and Pedroli 2006) to both the estuary and near-shore zone. This not only maintained natural sedimentary environments that provided unique and complex soft bottom habitats for a variety of fauna and flora (Fan and Huang 2004) but also provided suitable conditions to maintain highly productive systems, including the richest source of plankton in the Bohai (Liu and Pedroli 2006). These conditions supported rich fisheries resources and represented an important nursery area for many fish species.

Within the estuary, mixing of fresh and salt-water results in longitudinal salinity gradients. As a result, available habitats are partitioned for a variety of estuarine dependant biota based on their salinity preferences and/or tolerances. Salinity gradients are also important for migratory species (both anadromous and catadromous, see Figure 82). The longitudinal extent of this gradient not only provides an important olfactory cue for directional movement, but also allows fish to alter physiology gradually as the move between saline and freshwater habitats, or vice versa.

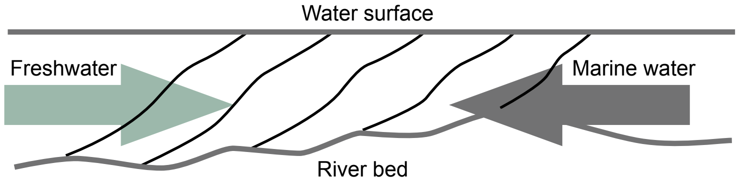
Habitat complexity in the estuarine reaches of the delta support a high diversity of fish species. Historically, migration of the river channel across the delta, together with the deposition of large quantities of sediment, provided a high diversity of tidal habitats including deep water, shallow water shoals, backwaters, small tidal channels and wetlands (Fan and Huang 2004; 2005). Natural succession of aquatic and semi-aquatic plant communities with these habitats also provided important habitats for fish, particularly small-bodied species and early life stages.

Flow regulation has resulted in substantial modification to these important features of the estuary and near-shore habitats. Since the 1970s, flow alteration involving reduced event frequency and duration, reduced baseflow magnitude and spells of cease to flow, particularly between March and June (Figure 41, Figure 43, Figure 44, Figure 48). The important season for plankton growth and reproduction has reduced primary productivity resulting in population declines of many marine and estuarine fish species. Furthermore, during cease to flow periods, nutrients became concentrated in remaining river pools and wetlands. This not only caused eutrophication within the river and associated wetlands, but also caused significant ‘red-tide’ algal blooms in near-shore habitats when high concentrations of nutrients were flushed from the catchment when the river flowed during July and August. Since the establishment of WSDR in 2002, nutrient transport to the estuary and near-shore habitats now coincides with suitable conditions for high primary productivity, and the risk of red-tide blooms has been reduced (Zhu 2006).

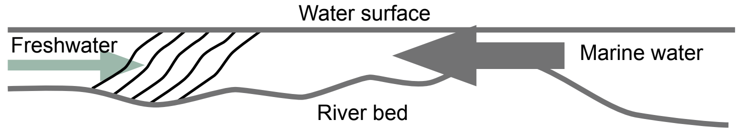
Modification of the water-sediment balance has also resulted in substantial modification of physical habitats, particularly a reduction in the complexity and variety sedimentary habitats and the fringing vegetation (Fan and Huang 2004; 2005). Although only limited information is available on the effects of flow alteration on salinity gradients, available evidence indicates that the reduction of river flows, since regulation, has resulted in salinisation of estuarine habitats (Qi and Luo 2007; Asian Development Bank 2008). Increased deposition of sediments on the delta (sediments usually flushed to the Bohai during high-flow events) is also expected to have modified salinity dynamics. A reduction in flow, particularly during spring and shallowing of the estuary mouth is likely to reduce mixing of saline and freshwaters and restrict tidal exchange within the estuary (Shu and Fei 2008). The combination of these has resulted in propagation of the salt wedge further upstream and a reduction in the longitudinal extent over which the salinity gradient occurs (Shu and Fei 2008) (Figure 83).

Figure 83. Representation of expected salinity gradient during the low flow season in the Yellow River estuary prior to flow alteration (A) and after flow alteration (B).

A.



B.



Width of arrows depict relative contribution of river (freshwater) and tidal (marine water) flows. Diagonal lines depict isohalines, or, the position and longitudinal extent of the salinity gradient.

The key flow related issues in the estuarine reaches and near-shore zone of the Yellow River Delta are:

- maintaining the supply of sediments to maintain complex physical habitats including deep water, shallow water shoals, backwaters, small channels and wetlands
- maintaining inundation regimes to main submerged emergent and water dependant terrestrial fringing vegetation
- avoiding excessive sedimentation of deltaic channels that may restrict tidal exchange
- maintaining river flows, particularly in spring, for the supply nutrients and maintenance of appropriate salinity gradients.

9.4 Representative fish flow dependent habitat requirements

9.4.1 The Yellow River northern bronze gudgeon (*Coreius septentrionalis*)

The Yellow River northern bronze gudgeon (*Coreius septentrionalis*) is a nationally protected species (second level; threatened in China Red Data Book; China Species Red List) (Yu D et al. 2010). It is considered to be moderately resilient with a minimum population doubling time of 1.4–4.4 years, and moderately to highly vulnerable (Froese and Pauly 2010).

This pelagic (mid-lower water column) freshwater species is endemic to the mid- to lower-reaches of the Yellow River where it lives in low to moderate-velocity habitats (Yue et al. 2010; Yu 1998). It is commonly found in shoals with moderate velocity and coarse substratum including sands, gravels and rocks (Yu D et al. 2010; Yue 1998). During winter it shelters under rocks in deeper areas or in ponds (Yue, 1998). Mature adults migrate upstream between May and July to spawn in clear (transparency to about 0.3 m) high velocity habitats (Yue, 1998) with stone/gravel substrates (Peng 2007, cited in Yu D et al. 2010) when water temperatures reach between 18 and 22 °C. Although moderate and high water velocities have been identified as important for adult habitat and spawning, these were not quantified.

Between the 1980s and 2002, the northern bronze gudgeon disappeared from the Yellow River and this was attributed to the substantial reduction in flow over that period (Sun, 2010). Since 2002, and the establishment of integrated sediment-water releases from Xiaolangdi Dam, the species has reportedly returned to the Yellow River (Sun 2010). However, a 2008 survey failed to record this species anywhere in the basin (Ru et al. 2010). Anecdotal reports of local fishers suggest that C. septentrionalis could be present in the upper Yellow River, near Lanzhou (Hui-Jun Ru, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, pers. comm., 2010).

The environmental flow requirements of the northern bronze gudgeon should be considered for reaches 1, 2 and 3. The key environmental flow requirements are:

- diversity in channel morphology including the presence shallow water shoals with coarse substratum (sand is the coarsest substratum in the lower Yellow River), as well as deeper habitats
- longitudinal habitat continuity between May and July to allow upstream spawning migrations
- availability of high water velocity habitats for spawning.

9.4.2 Yellow River carp (*Cyprinus carpio*)

The Yellow River carp (*Cyprinus carpio*), also known as common carp, is an iconic species in China's inland waters that is considered to be hardy, and tolerant of a wide range of environmental conditions. Nonetheless, within its natural range, it is considered to be moderately resilient with a minimum population doubling time of between 1.4 and 4.4 years with high to very high vulnerability (Froese and Pauly 2010).

The species generally favour large, fresh water bodies with low water velocities, or standing water (such as wetlands or ponds). They are omnivorous, feeding on a variety of aquatic insects, crustaceans, annelids, molluscs and vegetation. Although they are considered to have relatively wide habitat preferences (Froese and Pauly 2010), water depth and velocity thresholds for carp populations in the Yellow River have been previously described (Jiang et al. 2010). Adult fish prefer low velocity habitats, ranging over 0.1–0.8 m/s, and water depths greater than 1.5 m. For spawning, the depth and velocity requirements were described as > 1 m and <0.3 m/s respectively, and for juvenile stages as 1–2 m and 0.1–0.6 m/s respectively (Jiang et al. 2010). However, evidence from populations of the same species elsewhere (e.g. see Froese and Pauly (2010) and Edwards and Twomey (1982) and their references) suggest that these thresholds are conservative and that lower velocities and shallower depths may be sufficient to sustain populations in the lower Yellow River. For example, Edwards and Twomey (1982) described the range of maximum depth for carp during the spawning period as 0.45–2.0 m (although more commonly spawning occurs in depths <0.5 m); Conklin et al. (1996) observed carp in water depths of 0.03–0.76 m and velocities of 0–0.61 m/s; Borgstrom (2010) found that carp were mostly found in run habitats with depths of 0.55–0.85 m, and they had a preference for slower water with the 0.15 m/s class preferred, followed by the 0.05 m/s class. Also, Borgstrom (2010) observed that sand was the preferred substrate, followed by silt, and most carp were found in habitats without cover. In contrast, Jiang et al. (2010) indicated that grass cover was the preferred habitat for adult carp.

Spawning is consistent with other cyprinid species and occurs in spring and early summer (Panek 1987) (April– June) when water temperature reaches 17–18 °C and spawning ceases at a water temperature of 26–28°C (Edwards and Twomey 1982). Asian strains start to spawn when the ion concentration of the water decreases abruptly at the beginning of the rainy season (FAO 2011a). Adult females are highly fecund, laying up to 300,000 sticky eggs. Spawning occurs in shallow, low velocity habitats and eggs adhere to vegetation. Embryonic development takes 60–70 degree days. Hatched fry stick to substrate and live from yolk supplies. Three days after hatching the posterior part of the swim bladder develops, the larvae start to swim (Flajšhans and Hulata 2007). Best growth is obtained at water temperatures of 28–30 °C, although temperatures down to 23 °C are suitable (Edwards and Twomey 1982). The fish can survive cold winter periods (Flajšhans and Hulata 2007). Salinity up to about 5 per cent is tolerated, optimal pH is 6.5–9.0; common carp can survive low oxygen concentration (0.3–0.5 mg/L) as well as super-saturation (Edwards and Twomey 1982; Flajšhans and Hulata 2007; FAO 2011a). Wang and Yang (1986) suggested that sediment concentrations exceeding 40 kg/m^3 were lethal to the Yellow River carp, although Panek (1987) quoted a significantly higher figure of 165 kg/m^3. Edwards and Twomey (1982) cited a tolerance for turbidity greater than 200 turbidity units (JTU) and Secchi depth less than 8 cm. High turbidity water is common at spawning sites, and does not interfere with carp activity as long as food supply is not limiting (Edwards and Twomey 1982).

The environmental flow requirements of the Yellow River carp should be considered for reaches 1, 2 and 3. The key environmental flow requirements are:

- diversity in channel morphology including the presence of river associated backwaters and wetlands
- year-round availability of hydraulic habitat for adult fish with velocity < 0.8 m/s and depth > 0.5 m; perennial flow to maintain suitable habitats
- seasonal connection between the river and associated wetlands for spawning and recruitment migrations
- maintenance of submerged and emergent vegetation for habitat and spawning sites
- elevated flows during spring, April–June, (10–20 days duration) to cue spawning and inundate backwaters and wetland spawning sites, with temperature > 18 °C
- availability of, and open access to, inundated backwaters during spring, April–June, with depth 0.5 –1 m and velocity < 0.5 m/s.

9.4.3 Bighead carp (*Hypophthalmichthys nobilis*)

Bighead carp (*Hypophthalmichthys nobilis*) is a benthopelagic, potamodromous, freshwater species that lives in rivers with marked water-level fluctuations, and overwinters in the middle and lower stretches. It is able to tolerate water temperatures of 0.5–38 °C and high turbidity (FAO 2011b).

Information on the biology and habitat preferences of bighead carp can be found in FishBase (Froese and Pauly 2010). Bighead carp forages in shallow (0.5–1.5 m deep) and warm (> 24°C) backwaters, lakes and flooded areas with slow current; it is a bottom feeding fish. It undertakes long distance upriver migration at the start of a rapid flood and water-level increase (in April–July depending on locality, peak in May). Spawning grounds are usually located in river reaches characterised by turbulent or whirlpool-like flow, often in the vicinity of islands or stream junctions (Yih and Liang 1964). Bighead carp breeds in very deep, very turbid and warm water > 18 °C (usually 22–30 °C), with high current (1.1–1.9 m/s) and high oxygen concentrations. It spawns in the upper level of the water column or even at the surface during floods. Spawning ceases if there is a fall in the water level, and then it resumes when water level increases. After spawning, adults migrate for foraging habitats. Semi-buoyant eggs are laid that are maintained in suspension by turbulence. The eggs are thought to die if they sink to the bottom. Larvae drift downstream and settle in floodplain lakes, shallow shores and backwaters with little or no current. During autumn-winter, when temperature drops to 10 °C, juveniles and adults form separate large schools and migrate downstream to deeper places in main course of river to overwinter.

The environmental flow requirements of bighead carp should be considered for reaches 1, 2 and 3. The key environmental flow requirements are:

- diversity in channel morphology that creates large scale turbulent flow, such as associated with islands, major bars, and tributary junctions (i.e. the tributaries are required to have significant inflow to the main river)
- perennial flow to maintain suitable habitats
- year-round availability of hydraulic habitat for adult fish with low velocity and shallow depth 0.5–1.5 m.
- a rapidly rising and sustained flow pulse to stimulate spawning in April–July, with velocities of 1.1–1.9 m/s, depth > 2 m, and temperature > 18 °C
- following spawning, a flow of sufficient velocity (> 0.23 m/s) in the main river channel to maintain eggs in suspension.

9.4.4 Grass carp (*Ctenopharyngodon idellus*)

Grass carp, *Ctenopharyngodon idellus*, is a demersal, potamodromous, freshwater species. It occurs in lakes, ponds, pools and backwaters of large rivers, preferring large, slow-flowing or standing water bodies with vegetation. Grass carp is tolerant of a wide range of temperatures from 0–38 °C, salinities as high as 10 ppt, and oxygen levels as low as 0.5 ppm. This species prefers clear water but can tolerate high turbidity (Froese and Pauly 2010).

Information on biology and habitat preferences of grass carp was collated by Stanley et al. (1978), Shireman and Smith (1983) and Hassan-Williams and Bonner (2011). Grass carp normally dwell in the mid- to lower-layer of the water column. Grass carp spawn in large rivers with well-vegetated, flooded lowlands; spawning grounds are usually located in river reaches characterized by turbulent or whirlpool-like flow, often in the vicinity of islands or stream junctions (Yih and Liang 1964). Flowing water and changes in water level are essential environmental stimuli for natural spawning; a rise in water level of >1.2 m within a 12-hour period is thought to be required (Hassan-Williams and Bonner 2011), although a rise in water level of as little as 0.10–0.15 m could be sufficient in some rivers (Shireman and Smith 1983, p. 29). Movement for spawning begins in the period April–July (Jiang et al. 2010) when water temperature rises to 15–17 °C; spawning begins at 18 °C and peaks at 20–22 °C (Hassan-Williams and Bonner, 2011). Grass carp spawn on river beds with very strong current, in the range 0.7–1.8 m/s.

Semi-buoyant eggs drift 50–180 km before hatching (Shireman and Smith, 1983, p. 12). Leslie et al. (1982) showed that eggs were adequately transported by a current of 0.23 m/s. The larvae hatch one day after spawning and make their way to vegetated lagoons impoundments or floodplain lakes. They begin feeding on rotifers at 2 to 4 days and change to larger zooplankton in about a week. Temperatures required for stimulation of sexual maturation, egg incubation, and survival of young range from 19–30°C, with an optimum of about 23°C. Because the requirements for each environmental factor must be found in juxtaposition, successful reproduction occurs in only a few locations (Stanley et al. 1978).

The environmental flow requirements of bighead carp should be considered for reaches 1, 2 and 3. The key environmental flow requirements are:

- diversity in channel morphology that creates large scale turbulent flow, such as associated with islands, major bars, and tributary junctions (i.e. the tributaries are required to have significant inflow to the main river); also required are river associated backwaters and wetlands
- perennial flow to maintain suitable habitats
- year-round availability of hydraulic habitat for adult fish with low velocity or standing water, and aquatic vegetation
- seasonal connection between the river and associated wetlands for spawning and recruitment migrations
- a rapidly rising (>1.2 m within a 12-hour period) and sustained flow pulse to stimulate spawning in April–July, with velocities of 0.7–1.8 m/s, and temperature > 18 °C
- following spawning, a flow of sufficient velocity (> 0.23 m/s) in the main river channel to maintain eggs in suspension; temperature 19–30 °C.

9.4.5 Barbel chub (*Squaliobarbus curriculus*)

Barbel chub, *Squaliobarbus curriculus*, is a benthopelagic, freshwater fish. There is no information available on the biology and habitat preferences of this species in publicly accessible databases. In a study in the Zhaoqing section in the Pearl River, Tan et al. (2009) and Tan et al. (2010) found that barbel chub spawned mainly between July and September, but that spawning had been delayed one month by river regulation. Tan et al. (2009) noted that spawning activity was affected by the hydrological regime, but Tan et al. (2010) did not specifically mention barbel chub as one of the species strongly dependent on discharge for spawning. Chen et al. (2009) included barbel chub in a list of species found in the middle Yangtze River that are adapted to low velocity or standing water.

For this study, it was assumed that the requirements of barbel chub would be met by the same requirements of grass carp and bighead carp.

9.4.6 Saury, Chinese/taper-tail anchovy (*Coilia nasus* or *Coilia ectenes*)

The saury is an economically important pelagic-neritic, anadromous species (Figure 82) that lives in freshwater, brackish and marine environments. It occurs in coastal waters, estuaries and reaching up to the mid-reaches of rivers. It lives in water of moderate turbidity. Landlocked populations also occur (Yang et al. 2006; Li et al. 2007).

Saury spawns around three times in a lifetime; spawning occurs in-between reeds. In the Chikugo River, Japan, the fishes migrate about 15 km upstream and spawn in freshwater, the spherical eggs floating down and hatching near the river mouth. The fish reaches sexual maturity at 1–2 years of age (Zhao et al. 2007). Mature individuals migrate upriver and spawn in the lower and middle reaches of the Yangtze River and other coastal rivers in China (Ma et al. 2010). Spawning also occurs in the estuary, but females spawning in the estuary are smaller (and therefore less valuable for population recruitment) than those migrating to freshwater to spawn (Li et al. 2007). They also spawn in lakes adjacent to the Yangtze River, including Poyang and Taihu Lakes, where anadromous migrations have ceased and the fish have taken up permanent residence (Yang et al. 2006; Li et al. 2007; Ma et al. 2010). Spawning velocity and depth requirements are 0.7–1.4 m/s and 1–2 m, with a maximum of 1 m/s for the upstream spawning migration (Jiang et al. 2010). Spawning activity is correlated with increased river discharge (Zhong and Power 1996).

In China, the breeding period of saury is April to October (Zhao et al. 2007). From early February to the end of April adults move upstream into the Yangtze River and spawn in associated lakes in the Yangtze's middle and lower reaches (Ma et al. 2004; Li et al. 2007), while Jiang et al. (2010) assumed upstream migration occurred over the period April to June. Evidence suggests that spawning begins when water temperatures reach 19–22°C (Jiang et al. 2010). Although limited information on specific spawning sites exists, it is thought that sites within riverine lakes and wetlands, close to the mouths of their tributary rivers, provide appropriate spawning habitats. Prior to it being isolated from the main stem, Dongping Hu was thought to be the main spawning ground of saury in the Yellow River; other connected waterbodies, such as Kaifeng wetlands, were probably also used. In China, landlocked lake populations may spawn later than anadromous populations (Li et al. 2007; Ma et al. 2010). Peak breeding time is late spring and early summer (Li et al. 2007), or more specifically, June to August (Jiang et al. 2010). After spending up to three months in the spawning habitats, adults migrate downstream to marine habitats during the high flow season between July and October (Jiang et al. 2010). Larvae and young juveniles remain in freshwater habitats for an unknown period of time and prey on a variety of zooplankton. Information provided by the Scientific Panel of this project suggested that late-spawned larvae may spend the winter in natal habitats before migrating downstream to the sea the following year.

Adults prefer habitats with muddy or sandy substratum, water depth > 0.6 m and velocity less than < 1.0 m/s. Although the habitat requirements of juvenile stages are lesser known, it is thought that water velocities of about 0.4–0.5 m/s are preferred (Jiang et al. 2010).

Poor water quality and hydrological alteration since the 1970s, particularly the frequent occurrence of long-duration cease-to-flow events, restricted the upstream spawning migrations and isolated mature adults from their preferred spawning grounds. In subsequent years, population numbers decreased and the sustainability of the species was threatened (Ru et al. 2010). Alteration to salinity dynamics in the estuary may also have inhibited the upstream spawning migration of adult *C. ectenes*. For example, based on knowledge of the estuarine spawning requirements (Chen and Huang 1963), Yu (1983) predicted that spawning of the closely related *C. mystus* would be impacted by reduced freshwater flows reaching the Yangtze River estuary, and the subsequent reduction in the extent of the salt wedge and availability of preferred spawning salinities within the estuary. Nonetheless, Yu (1983) found no close relationship between river runoff and the catch of several migratory fish species[26], including *Coilia ectenes*. This study did show, however, a relationship between discharge and relative abundance of year classes, suggesting that while spawning migrations may not be affected, spawning and recruitment may be. In particular, it was suggested that

26 Correlation was between total winter discharge (from November–January) before fish enter the Yangtze River and the amount of fish caught after they enter the river.

under conditions of higher freshwater inflows, suitable estuarine salinity dynamics (concentration and extent) favoured successful spawning (fertilsation) and recruitment, and also maximised habitat available to new recruits. While the evidence of Yu (1983) illustrates the importance of freshwater inflows to anadromous and estuarine dependent species, their specific requirements for salinity, habitat and other resources (e.g. food) remain poorly understood.

Sun (2010) suggested that since 2002, and the establishment of sediment water releases from Xiaolangdi Dam, *Coilia ectenes* has returned to the lower Yellow River. However, a survey in 2008 by Ru et al. (2010) failed to record the presence of this species.

The environmental flow requirements of saury include requirements relevant to all four reaches. The key environmental flow requirements are:

- maintaining perennial baseflows to provide habitat continuity between the marine and freshwater habitats and provide adults with access to spawning grounds located in river associated wetlands
- sustained flow pulse during spring (April–June) with velocity < 1 m/s to cue upstream spawning migration of adults (including the establishment of appropriate salinity gradients in the estuarine reaches)
- providing appropriate habitats for spawning in June - August (depth 1–2 m, velocity 0.7–1.4 m/s and water temperature 19–22°C) in the Dawen River delta within Dongping Hu, and in riverine wetlands (Kaifeng, Zhengzhou and Mengjin)
- high-flow pulse during summer (July–October) to cue downstream migration of adults and juveniles to marine habitats
- year-round provision of appropriate wetland habitats (Kaifeng, Zhengzhou and Mengjin) for adults and early life stages (water depth > 0.6 m and velocity less than < 1.0 m/s)
- appropriate water and nutrient regimes in wetlands to maintain important season prey (zooplankton) for adults and new recruits over the spring–summer period.

9.4.7 Japanese eel (*Anguilla japonica*)

The Japanese eel, *Anguilla japonica*, is a commercially valued catadromous species, often used in Chinese medicine (Froese and Pauly 2010). Information on the biology and habitat preferences of Japanese eel can be found in FishBase (Froese and Pauly 2010) and FAO (2011c). Adults live and spawn in marine habitats. Young Japanese eels enter rivers in small shoals from February to May, and ascend into favourable freshwater habitats. These habitats are utilised for several years, until sexual maturity is reached, where upon adults migrate downstream and enter the sea from August to October. The Japanese eel is considered to have a flexible pattern of migration, with an ability to adapt to various habitats and. These migrations into freshwater are not an obligatory migratory pathway, and this form of diadromy should be defined as facultative catadromy (Tsukamoto and Arai 2001).

Information on the hydraulic and hydrological requirements of this species was provided by Jiang et al. (2010), although the original data sources were not cited. During the upstream migration from the Bohai to freshwater habitats (February to May) and for the duration of their freshwater lifecycle, juvenile and sub-adult eels are thought to prefer water depths > 1.0 m and velocity between 0.3 and 0.5 m/s. Nonetheless, it should be noted that the species has the ability to move over land at night or during moist conditions from one place to another (Froese and Pauly 2010). Shiao et al. (2003) reported that in Taiwan, fishermen's experience has indicated that *A. japonica* is dominant in the lower reaches of rivers and in estuaries. Sampling of eels in four Taiwanese rivers by Shiao et al. (2003) confirmed this intuitive knowledge. *A. japonica* preferred sandy and muddy substrates with shelters; shallow water and fast current were *not* attractive to this species. Eels of different size also differed in habitat preference. The larger eels tended to reside in deep pools in the upper reaches, but small eels chose shallow waters in the lower reaches of rivers. Shiao et al. (2003) speculated that cease-to-flow conditions may negatively influence the migratory behaviour and habitat use of the eel by confining it to isolated, deep pools and interrupting their movement between pools.

The environmental flow requirements of Japanese eel include requirements relevant to all four reaches. The key environmental flow requirements are:

- providing appropriate habitats for juvenile and adult stages (depth > 1.0 m and velocity < 0.5 m/s)
- maintaining longitudinal connectivity between freshwater and marine habitats during February to May and August to October for recruitment and spawning migrations respectively
- perennial flow to maintain suitable habitats.

9.4.8 Small-bodied species

Although the Yellow River is inhabited by numerous small-bodied species, information on their flow and habitat requirements is limited. Two cyprinid species, *Hemiculter leucisculus* and *H. bleekeri*, as well as a variety of loach (Cobitidae) were identified by the Scientific Panel for this project as significant species in freshwater or estuarine habitats of the lower Yellow River. In general, these species are permanent residents of freshwater or estuarine habitats and prefer low velocity habitats, particularly in permanently inundated river associated wetlands and backwaters. Many of these species are omnivorous, such as *H. leucisculus*, which relies on macroinvertebrates, zooplankton, crustaceans and algae as primary food sources (Dulmaa 1999; Froese and Pauly 2010). This species is also believed to scatter its eggs in open water or on the substrate (Breder and Rosen 1966); however, no other information on the flow or habitat requirements for spawning has been documented. In contrast, *H. bleekeri* feeds on vegetation that becomes inundated on gently sloping littoral habitats, particularly during increases in water level (Dudgeon, 1983), although the requirements for timing, if any, have not been documented. Based on work undertaken in the Yangtze River (Li et al. 2009), this species is expected to be locally abundant and contribute substantially to fish diversity in the lower reaches of the Yellow River.

Several cobitids (loach), including spined loach (*Cobitis taenia*), Oriental weatherloach (*Misgurnus anguillicaudatus*) and *M. mizolepis* have been recorded in freshwater habitats of the Yellow River. Cobitids generally prefer low velocity habitats with fine sand and mud substrates (Froese and Pauly 2010) in which several species bury themselves for shelter. Submerged plants, and detritus are also important, providing habitat for adults and suitable spawning sites. Spawning generally occurs in spring and eggs are attached to either the substrate of submerged plants/detritus in areas with some flow (Froese and Pauly 2010).

The flow requirements of small-bodied species that inhabit low velocity habitats should be considered in all three freshwater reaches (reaches 1, 2 and 3). The key environmental flow requirements are:

- habitat complexity, particularly the maintenance of low velocity backwaters and river associated wetlands
- permanent, or regular, connection between the main channel and associated wetland/backwater habitats
- maintenance of submerged, emergent vegetation as habitat and spawning sites
- availability of substrates with fine particle sizes e.g. fine sands and muds
- perennial flow to maintain suitable habitats.

9.4.9 Catfish species (Bagridae)[27]

Several species of catfish (Bagridae), such as the yellow catfish (*Pelteobagrus fulvidraco*) and the ussuri catfish (*Pelteobagrus ussuriensis*) are known from the Yellow River catchment. Both are non-migratory freshwater species that inhabit both main channel and wetland habitats. Members of the Bagridae family are generally benthic feeders. The yellow catfish is a good example, and feeds predominantly on aquatic insects (trichopterans and chironomids), molluscs, as well as cladocerans and zooplankton (Cao et al. 2009). Many catfish species are nest builders, in which they spawn and subsequently guard their eggs. Nests are often constructed from coarse particle sizes including sands and gravels and positioned in areas with some water flow so that eggs remain well aerated for the duration of development. Although limited information is available on the spawning requirements of catfish in the Yellow River, it is thought they also build nests (Jiang et al. 2008) and have similar requirements for substrate and flow as described above. In the Yellow River, catfish spawn during spring (April–June), which is consistent with peak spawning time of the same species in other areas of central China (Cao et al. 2009). It is thought that increases in both river flow and water temperature are important spawning cues.

The flow requirements of Bagridae catfish should be considered in reaches 1, 2 and 3. The key environmental flow requirements are:

- sufficient water velocities to maintain coarser substrates of sands and gravels required for nest building
- increases in flow and water temperature for spawning cue
- sufficient water velocities over nesting sites to aerate eggs.

27 e.g. yellow catfish (Pelteobagrus Fulvidraco) and ussuri catfish (P. ussuriensis)

9.4.10 Estuarine dependent small bodied fish

While there are many small-bodied fish species that live in the estuary of the Yellow River, little is known of their biology or requirements for habitat. Two gobid species, the Asian goby (*Synechobius ommaturus*) and *Chaeturichthys stigmatias* were identified by the Scientific Panel for this project as potentially important species in the Yellow River estuary. Both these species prefer shallow, soft bottom sediments dominated by sands and muds and are expected to use seasonally or tidally inundated areas adjacent to the main waterbody (Froese and Pauly, 2010). They mainly prey on shrimp and fish eggs and larvae (noted by the Scientific Panel). Spawning occurs from mid-April to early-June, when eggs are deposited on consolidated sandy substrates that are available during periods of low river flow. Increases in river discharge during spring are thought to represent important spawning cues (noted by the Scientific Panel).

The flow requirements of small bodied estuarine fish, such as members of the Gobidae family*,* should be considered in reach 4, and possibly reaches 2 and 3. The key environmental flow requirements are:

- availability of soft sand-mud substrates
- increases in flow and water temperature mid-April to early-June for spawning cue
- sufficient water velocities over nesting sites to aerate eggs
- maintaining appropriate salinity dynamics, primarily longitudinal salinity gradient with the estuary and lower riverine reach
- continuous flow, including delivery of nutrients during high flows to promote estuarine productivity (plankton, zoobenthos, calanoid copepods etc.).

9.4.11 Estuarine dependent large-bodied fish

A variety of large bodied fish use estuarine reaches of the Yellow River, either as permanent residents, or seasonally for spawning, and/or recruitment. Mugilids (mullets) are economically important and two species were identified by the Scientific Panel for this project as occurring in the Yellow River, namely, *Liza haematocheilus* (sp-iny mullet) and *Mugil cephalus*. *L. haematocheilus* is a catadromous species (Figure 82) capable of living in the lower freshwater and estuarine reaches. Adults migrate downstream to spawn at sea and juveniles subsequently re-enter estuarine and freshwater habitats (Froese and Pauly 2010). The species is considered omnivorous and to rely on vegetation, zoobenthos and detritus (Froese and Pauly 2010). In contrast, *M. cephalus* is an estuarine dependant species, although its use of estuaries is not obligatory; it can complete its life cycle in marine habitats when no estuaries are accessible by juvenile stages. The species, used in Chinese medicine (Tang 1987), enters estuaries opportunistically as adults, and during juvenile life stages to use sandy and muddy habitats (Eschmeyer et al. 1983). The species feeds on zooplankton as larvae, detritus, micro-algae and benthic organisms as juvenile and adult fish (Froese and Pauly 2010). Both species recruit to estuarine and/or lower freshwater habitats as sub-adults (1^+ years of age). This recruitment takes place during periods of low flow.

Chinese perch (*Lateolobrax japonicus*) was also identified by the Scientific Panel for this project as an important, large bodied estuarine fish. This species spawns in near-shore habitats during winter and can live deeper areas of the lower Yellow River and estuary. It is a predatory species, feeding on zooplankton during early life and on small fish and shrimps as adults (Sun et al. 1994). As a predatory fish, it is expected to prefer reasonable water clarity, although it is known to inhabit very turbid waters, particularly during the high flow period (Sun et al. 1994). Chinese perch are usually found in, or around areas with dense macrophytes. Although not considered dependent on estuarine habitats, migration of larval and juvenile stages into estuaries and lower riverine reaches allows early life stages to exploit productive foraging grounds with higher prey biomass (particularly calanoid copepod), elevated temperature and reduced salinity. This life strategy may reduce mortality and increase condition and growth of early life stages (Islam et al. 2006a; 2006b).

The flow requirements of large bodied estuarine fish should be considered primarily in reach 4, and possibly reaches 2 and 3. The key environmental flow requirements are:

- availability of soft sand-mud substrates
- maintaining appropriate salinity dynamics, primarily the longitudinal salinity gradient within the estuary
- continuous flow, including delivery of nutrients during high flows to promote estuarine productivity (plankton, zoobenthos, calanoid copepods etc.)
- maintaining deep-water habitats in the lower reaches and estuary.

9.5 Fish-based flow objectives

A number of fish flow objectives were derived from consideration of the needs of key species representing the five fish groups based on life history strategies. The objectives were specific to particular species and function (Table 31), and each objective was expressed in terms of hydraulic/hydrologic criteria, frequency/duration and location (Table 32). Some of the hydraulic and hydrological criteria will be described in detail following hydraulic modelling of the river.

Table 31. Fish-based flow objectives – relevant species and function.

No.	Objective	Relevant species	Function
F1	Maintain low flow habitat continuity through perennial flow	All species	Habitat maintenance
F2	Maintain shallow habitats with moderate-high velocity for shallow water dwelling species, and spawners during low flow periods	Northern bronze gudgeon; Yellow and ussuri catfish	Resident habitat and/ or spawning habitat
F3	Facilitate downstream migration of diadromous species by allowing free passage	Saury; Japanese eel	Life cycle/ migration requirement
F4	Maintain sufficient water depth in pools for large bodied fish	Big head carp and grass carp; Barbel chub; Chinese perch	Habitat maintenance
F5	Stimulate spawning, migration (anadromy and potadromy) and maintain habitat continuity between near-shore/estuarine and freshwater habitats to allow free upstream passage; inundate high flow backwaters and river associated wetlands	Northern bronze gudgeon; Saury (anadromy); Yellow River carp, big head carp and grass carp; Barbell chub (potadromy)	Spawning, spawning migration (upstream)
F6	Provide suitable habitats for spawning, and the development and recruitment of early life history stages by allowing access of large bodied fish to backwater and wetland habitats with abundant submerged vegetation	Saury (anadromy); Yellow River carp, big head carp and grass carp; Barbel chub (potadromy)	Spawning, embryonic development and larval-juvenile recruitment
F7	Maintain downstream transport of semi-buoyant eggs within the water column	Big head carp and grass carp; Barbel chub (potadromy)	Egg development and downstream transport
F8	Maintenance of appropriate salinity gradients in estuarine reach during spring for anadromous spawning migration	Saury; Japanese eel	Life cycle/ migration requirement
F9	Maintain sufficient water depths in pools and wetlands for large bodied fish	Japanese eel, Yellow River carp, big head carp and grass carp; Barbel chub (potadromy)	Adult habitat
F10	Maintain permanent/regular, low water velocity habitats with abundant submerged/emergent vegetation and/or fine sediments in river associated backwaters and wetlands for small bodied species	Sharpbelly and Cobitids	Habitat
F11	Maintain productivity (phytoplankton, zoobenthos, calanoid copepods) in lower riverine reaches and the estuary	Estuarine dependents and migratory species; Mullets; Chinese perch; Asian Goby	Estuarine productivity
F12	Maintain low velocity littoral habitats for small bodied species, particularly Cobitids	Spined and Oriental weather loach	Adult habitat
F13	Maintain shallow pool crossings with moderate-high velocities and coarser substratum (sands)	Northern bronze gudgeon; Big head carp and grass carp; Barbel chub	Habitat
F14	Maintain submerged aquatic vegetation, e.g. *Vallisneria*, *Potomageton* and *Myriophyllum* spp.	Big head and grass carp; Barbel chub; Spined and Oriental wheather loach	Habitat
F15	Maintain aquatic emergent vegetation, e.g. *Phragmites* and seasonally submerged meadow vegetation	Big head and grass carp; Barbel chub; Spined and Oriental wheather loach	Habitat
F16	Maintain minimum 2 mg/L dissolved oxygen, particularly in deeper pools	all	Habitat
F17	Maintain unconsolidated soft-bottom, substrates in estuarine backwaters and tributaries	Estuarine dependant species (*Synechobius ommaturus*)	Habitat
F18	Maintain sediment scour, tidal flushing and associated salinity dynamics to support estuarine dependant species	Estuarine dependent, catadromous and anadromous species	Habitat

Table 32. Fish-based flow objectives – flow specifications, and relevant reaches.

No.	Flow component	Hydraulic/hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing	Reach
F1	Cease to flow; Low flow	Q ≥ YRCC warning standards of low flow emergency; maintain area‡ ≥ critical depth* at pool crossings (specified each month)	Continuous	≥ 75% of the time	All year	All reaches
F2	Low flow	Maintain area‡ ≥ critical depth* with V ≤ 2.0 m/s[1,2]	Continuous	≥ 75% of the time	All year	Reaches 1– 3
F3	High flow, high-flow recession	Maintain longitudinal connectivity and area‡ ≥ critical depth* over barriers (shallow areas)	Continuous	≥ 75% of the time	Jul-Oct	All reaches
F4	Low flow	Maintain area‡ with depth ≥ critical depth* in pools	Continuous	≥ 75% of the time	Nov-Mar	Reaches 1– 3
F5	High-flow pulse	Achieve area‡ with depth ≥ critical depth* over barriers (shallow areas)	≥ 1 per year / 10 – 20 days[1]	≥ 4 in 5 years	Apr-Jun	All reaches
F6	High flow	Maintain area‡ with D = 0.5 – 1.0 $m^{1,2}$ and V ≤ 1.4 m/s[1,2]	Continuous	≥ 75% of the time	Apr-Sep	All reaches
F7	High flow	Maintain area‡ with velocity 1.0 – 2.0 m/s[1]	Continuous	≥ 75% of the time	Apr-Sep	All reaches
F8	High-flow pulse	Maintenance of appropriate† salinity gradient in estuary	≥ 1 per year / duration to be determined*	≥ 4 in 5 years	Apr-May	Reach 4
F9	Low flow and high flow	Maintain area‡ of D ≥ 1.5 $m^{1,2}$ and V ≤ 1.0 m/s[1,2]	Continuous	≥ 75% of the time	All year	All reaches
F10	Low and high-flow pulses	Achieve sufficient depth* to replenish/maintain water in river associated wetlands and backwaters	≥ 2 per year / ≥ 1 day	≥ 4 in 5 years	Jun-Nov and Dec-May	Reach 1
F11	Low flow and high flows	Maintain adequate cross-sectional area/discharge* to transport nutrients required to sustain primary productivity	Continuous	≥ 75% of the time	All year	Reaches 3 and 4
F12	Bankfull	2,600 - 4,000 m^3/s – see Geomorphologic objective G1	≥ 1 per year / ≥ 1 day*	≥ 4 in 5 years	Jun–Sep	Reach 1
F13	Bankfull	2,600 - 4,000 m^3/s – see Geomorphologic objective G2	≥ 1 per year / ≥ 1 day*	≥ 4 in 5 years	Jun–Sep	All reaches
F14	High flow	See Vegetation objective V1	Continuous	≥ 75% of the time	Jul–Oct	Reach 1
F15	High flow and low flow	See Vegetation objective V7	Variable	≥ 75% of the time	All year	Reach 4
F16	Low flow	Maintain mean pool velocity ≥ 0.01 m/s	Continuous	≥ 75% of the time	Nov–Mar	All reaches
F17	High flow and low flow	Sufficient discharge* to maintain morphology in and around the estuary mouth	Continuous	≥ 75% of the time	All year	Reach 4
F18	Bankfull	2,600 - 4,000 m^3/s – see Geomorphologic objectives G3 and G4	≥ 1 per year / ≥ 1 day*	≥ 4 in 5 years	Jun–Sep	Reach 4

‡ 'maintain area' means provide a percentage of the pre-dam area or an arbitrary area to be decided by the Scientific Panel on the basis of hydraulic/hydrologic analysis; * Tentative – to be refined on the basis of hydraulic/hydrologic analysis; † Data not available to determine criterion at this stage; 1. Personal communication, staff at Wuhan CAS Hydrobiology; 2. Jiang et al. (2010).

Chapter 10. Macroinvertebrates

10.1 Introduction

Macroinvertebrates are recognised as important components of riverine and wetland systems through their role in detrital processing (McQueen et al. 1986; Hall et al. 2003) and their contribution to food resources for a variety of fauna, including fish (Keast 1985) and birds (Salgado et al. 2007). Macroinvertebrates are widely used as indicators of environmental change (Chessman 1995; Parsons and Norris 1996) and for assessing ecosystem health of rivers (Ormerod and Edwards 1987) due to the sensitivity of some taxa to a variety of disturbances including flow alteration. Until recently, the common belief that the Yellow River supported relatively depauperate aquatic fauna populations (Liu et al. 2006), due to a variety of disturbances, was largely unsubstantiated by quantitative data. More recently, a study by Zhao et al. (2010) described macroinvertebrates in the Yellow River and identified a variety of disturbances influencing these communities.

10.2 Characteristics of macroinvertebrate assemblages

A total of 74 taxa belonging to 28 families and 56 genera were recorded from 21 sites in the upper, middle and lower Yellow River (Zhao, 2010). Assemblages in riverine reaches (including impoundments) comprised 17 taxa of oligochaetes, 48 taxa of aquatic insects, five taxa of molluscs, and four taxa of other animals. Many of the species recorded in the Yellow River are common in Chinese freshwaters and are widely distributed throughout river catchments (Morse et al. 1994).

A range of feeding guilds is represented in the Yellow River basin, including, collector-gatherers, predators, scrapers, shredders and collector-filters (Zhao 2010). Oligochaetes and collector-gatherers represent the dominant taxon and feeding groups throughout the basin. Nonetheless, assemblages vary spatially; oligochaetes dominate assemblages in upper reaches, insects dominate in middle reaches and other animals dominated in lower reaches. In the middle reaches and lower reaches (downstream of Xioalandgi Reservoir), Zhao (2010) recorded 42 taxa and 35 taxa respectively.

The study by Zhao (2010) identified important species in the mainstem of the river as *Nais communis* and *Acalcarella* sp., which dominated total macroinvertebrate density and *Branchiura sowerbyi* and *Exopalaemon modestus* dominated total biomass. The middle and lower reaches of the Yellow River are characterised by relatively low macroinvertebrate densities and biomass, and assemblages are dominated by predators and shredders.

Only limited information is available for macroinvertebrates assemblages in wetlands and the estuary. Although Wang X et al. (2008) described high insect diversity in a river-associated wetland in the middle Yellow River (Yinchuan, Ningxia), their collections appear to be of terrestrial life forms rather than aquatic life stages. Nonetheless, they identified Diperta (true flys) as the dominant taxa with in the wetland system, with diversity and abundance highest in July.

Chinese shrimp (*Penaeus orientalis* or *Penaeus chinensis*) is a highly valued inshore (estuarine) species that is mainly distributed in the Bohai and Yellow Sea and is seldom observed in the East China Sea and South China Sea; the major spawning ground of Chinese shrimp is in the three bays (Laizhou Bay, Bohai Bay and Liaodong Bay) of the Bohai (Jin 2008) (Figure 84). Acetes shrimp (*Acetes chinensis*) is the most abundant species in its genus, and is only distributed in the South and East China Seas and the Yellow/Bohai seas. It is the most important species in catch by fixed nets. The stock of Acetes shrimp is in good condition, with annual landings following an increasing trend (Jin 2008).

In a biological assessment of the Yellow Sea Ecoregion, Jin (2008) listed Chinese shrimp as important under four of eight possible criteria:

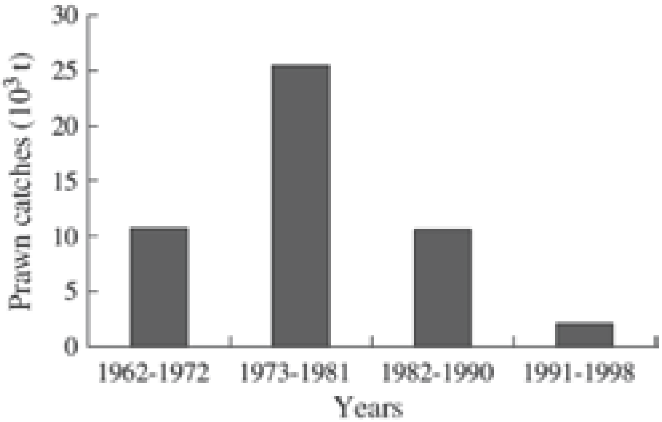
- representative species
- species of special concern 1 (threatened, depleted stocks and/or protected species)
- commercially important (value)
- changes in biological characteristics (reduced genetic diversity).

Figure 84. Ecologically important areas for Chinese shrimp (*Penaeus chinensis*) in the Yellow Sea Ecoregion.

Source: modified from (Jin, 2008).

Fan and Huang (2008) plotted the mean annual Chinese shrimp catches in the Bohai in autumn flood seasons in the periods 1972–1972, 1973–1981, 1982–1990 and 1991–1998 (Figure 85). The high catch occurred during 1973–1981, and the low one in 1991–1998. The high value for 1971–1981 was explained by overfishing, while reduction in nutrient loads and flow were thought to have caused the fall in shrimp catches in the 1980s and 1990s. Qiu et al. (2008) examined the variability of fish production in the East China seas, and their data (from 1956 to 1985) included Chinese shrimp and Acetes shrimp. While the trends in catch were attributed to growth in fishing effort, variations in catches through time were related to precipitation and monsoon wind speed. Correlations of catch variations with the physical variables suggested that land-based runoff and monsoon circulation of the diluted coastal water masses were the physical forces dominating catch variability, with the influences being exerted largely through the associated nutrient supply on primary production (Qiu et al. 2008).

Figure 85. Variations in the mean annual Chinese shrimp (*Penaeus chinensis*) catches in the Bohai during autumn floods (1962–1998)



Source: Fan and Huang (2008), using data from Huang and Su (2002).

10.3 Environmental influence on macroinvertebrate assemblages

Examination of the influence of environmental conditions on assemblage structure can provide important insights into important flow-related controls. Zhao (2010) differentiated five distinct groups of sites sampled in the upper, middle and lower Yellow River based on macroinvertebrate assemblage structure. These included: sites downstream of reservoirs, vegetated sites, reservoir sites, polluted sites, and lower-reach sites. Interestingly, macroinvertebrate assemblages at sites located immediately downstream of reservoirs and those with remnant riparian vegetation were distinctive in that both species richness and abundance were dominated by insect taxa. The distinctiveness of these assemblages was attributed to sediments dominated by coarser particle sizes including boulder, cobble and coarse sand, and the presence of riparian vegetation. Macroinvertebrate assemblages in the lowest reach (Lijin to Kenli) were also distinctive, being attributed to higher river discharges and finer sediments (fine sands). Macroinvertebrate assemblages in these sites displayed very low species richness and abundance (Zhao 2010).

Lower macroinvertebrate taxa number, density and biomass in the Yellow River, compared to other similar rivers, was attributed by Zhao (2010) to modification of the sediment-water balance and associated disturbance of benthic habitats. Water quality attributes contributing to pollution (total nitrogen, and total phosphorus), sediment concentration, and stability and compaction of substrate combined to influence the distribution of macroinvertebrates observed by Zhao (2010).

The life cycle of the Chinese shrimp was described by FAO (1997). The overwintering population of Chinese shrimp in the Yellow Sea starts to migrate northward in late-March arriving a month later in the spawning grounds in the estuaries along Bohai Sea and the southern coast of the Yellow Sea. The earliest and latest spawning dates are 2 May and 18 May respectively, when the sea bottom has temperatures of 15 to 18°C and salinities of 23 to 30‰. It takes about 12 days from spawning to the post-larvae stage when the shrimp migrate from the marine environment towards the estuaries, which are rich in nutrients and low in salinity. From June onwards, these coastal shallows act as nursery grounds for the post-larvae. By late August when the juvenile prawns reach 60 to 100 mm body length, they start to move to deeper waters for food. In September when they are 150 mm long, they move in groups or schools to waters over 20 m deep. By mid-November when the bottom waters of Bohai drop to 12 to 13°C, the prawns start moving southward in schools and reach the Yellow Sea wintering grounds up to 1000 km away in late January. There they disperse and embark on the reverse migration to the spawning grounds in the second half of March as temperatures start to warm. Thus, there are two distinct fishing seasons in the Bohai based on the life cycle – in spring (spawning population) and autumn (feeding-growing phase).

Studies have reported strong and significant relationships between Chinese shrimp recruitment in the Bohai in the flood season and the river runoff and the salinity/temperature in the nursery ground (Deng and Zhuang, 2002; Huang and Su, 2002). In a survey by Chen et al. (1997), the highest biomass of total set-net fisheries in the Yellow and Bohai Seas was in spring at (49.6 per cent), then autumn at 34.25 per cent, then summer at 11.25 per cent, and finally winter at 4.9 per cent. For Acetes shrimp, none were recorded in winter, with the majority recorded in spring, followed by autumn. Thus, in accordance with the lifecycle of the Chinese shrimp, the period of rising-river discharge in spring–summer (June–August) is the most important for environmental flow considerations.

Sun and Yang (2010) set environmental flow objectives in terms of target salinities and river discharge for spawning of Chinese shrimp. The critical period of the life cycle for salinity was given as June–July. The preferred depth range was 1–5 m, and the preferred salinity range was 8.8–25.8 per cent. Cai and Wang noted that Chinese shrimp grow well in aquaculture farms with salinities of about 5 per cent and under higher salinities the shrimp suffered from disease. In contrast, Dong et al. (2002) reported that the highest growth rate in Chinese shrimp occurred at 20 per cent salinity, with a suitable range being 20–28 per cent. Yu and Chen (1985) exposed Chinese shrimp post-larvae to water of different salinities for 12 days and found that growth was reduced when salinity exceeded 34.7 per cent. The salinity range of high growth rate was 11.32–31.08 per cent. The experiments of Miao and Tu (1996) revealed that for optimum daily growth rate of Chinese shrimp, daily temperatures would fluctuate between 30 and 32 °C. Similarly, FAO (1978) reported that penaeid shrimp spp. production was highest over the temperature range 26 to 30°C, with a maximum desirable temperature being 32°C.

Using a hydrodynamic model of the Yellow River estuary, Sun and Yang (2010) established a relationship between salinity (*S* in ‰) and daily freshwater inflows (*Q* in m^3/s):

$$S = 37.508\ e^{-0.001Q} \qquad (R^2 = 0.9932)$$

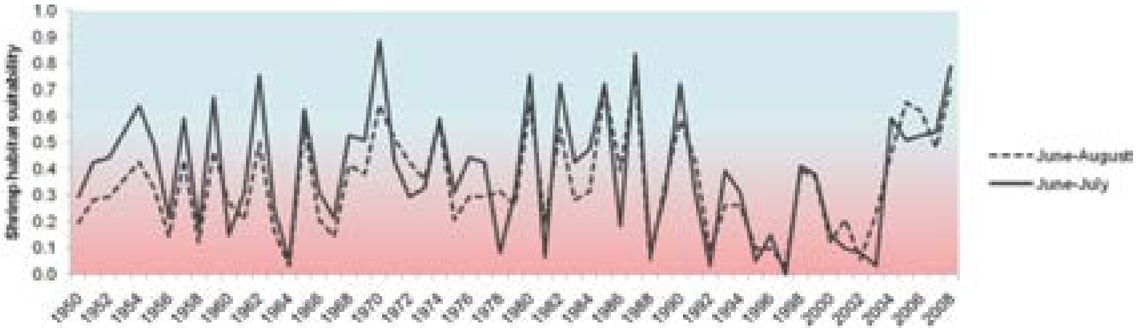
Sun and Yang (2010) did not state the location in the estuary where this relationship applied. Based on the salinity and depth criteria, Sun and Yang (2010) were able to model the time series of Chinese shrimp habitat availability as a function of monthly discharge, according to three levels of ecological objectives (high, medium and minimum). It was concluded that the managed flow regime from 2001 to 2005 met only the minimum water requirements of the shrimp.

The salinity-flow relationship of Sun and Yang (2010) was used to evaluate the time series of suitability of salinity in the estuary for Chinese shrimp rearing over the period of available daily discharge data from Ljin (1950-2008). For this evaluation, the preferred salinity range was 11–31 per cent (based on the above literature review), and the evaluated months were July to August, which corresponds to the period when shrimp are in the estuary for rearing; at other times shrimp are in the marine environment. The adopted salinity range is equivalent to a discharge range of 191–1227 m^3/s at Lijin. The model simply evaluated salinity conditions on any day as suitable or unsuitable, as the literature does not indicate that Chinese shrimp has a preference for the low or high end of the preferred salinity range. The suitability index of any year was calculated as the total number of suitable days in the period June-August (also June–July) as a proportion of the total number of days in this period, giving a score ranging from 0 to 1. It was assumed that temperature was always within the tolerable range; this assumption was based on data from 1994 to 2009 (Figure 76). This evaluation produced a similar result whether June-July or the longer June–August rearing period was considered (Figure 86). The time series showed that prior to the beginning of operation of Xiaolangdi in late-1999, Chinese shrimp rearing habitat suitability was highly variable from year to year, sometimes due to higher than preferred flows, and sometimes due to lower than preferred flows. The period 1992 to 2003 was characterised by generally poor habitat suitability due to low baseflows in the rearing period, while the suitability improved markedly in 2004 when higher baseflows were released from Xiaolangdi (Figure 86). Chinese shrimp habitat suitability was maintained at historically high levels from 2004 onwards.

10.4 Key flow dependence of macroinvertebrates

Comparison of the data gathered by the 2008 survey of Zhao (2010) with the limited information on macroinvertebrate assemblages collected previously highlights some interesting trends relevant to the assessment of environmental water requirements for the lower reaches of the Yellow River. In comparison with the data of Zhao (2010), who found 74 taxa in the basin, a total of 25 and 71 taxa were recorded in 1959 (Institute of Zoology Chinese Academy of Sciences 1959) and 1986 (Investigation Group of Fishery Resources of the Yellow River System 1986) respectively. Thus, there was a notable increase in taxa number between the 1959 and 1986 surveys, and there was another small increase evident in the 2008 survey data of Zhao (2010) (gastropoda and crustacean were the exceptions).

Figure 86. Variations in the annual Chinese shrimp (*Penaeus chinensis*) rearing habitat suitability (based on estuarine salinity preference).



Habitat suitability calculated for the June-August and June-July period.

The data of Zhao (2010) suggested that the primary influences on macroinvertebrate assemblages in the Yellow River Basin were sediment concentration, pollution levels and altitude. Extensive agricultural and industrial development along the middle and lower reaches of the Yellow River since the 1970s extensively modified the sediment-water balance, integrity of riparian vegetation, and water quality (Ni and Han 2005; Zhang and Zhang 2008). At least up until year 2000, substantial bed aggradation, a reduction in discharge capacity, loss of lateral connectivity with the floodplain, and impaired longitudinal connectivity (due to cease to flow events) (Liu 2006; Liu et al. 2006) were the main disturbances likely to have affected macroinvertebrates. Prior to the 2008 survey of Zhao (2010), macroinvertebrate surveys (noted above) were conducted under modified environmental regimes. Under the period of the Great Leap Forward (1958 to 1961) the irrigated area in the Yellow River basin increased by a factor of 58 (Bin et al. 2003). In 1959, 1960 and 1961 the volume of water diverted from the lower Yellow River rose dramatically (Figure 36). Also, Sanmenxia Dam was constructed during this period, with work beginning in April 1957 and the project completed and put into operation in October 1960 (Chen and Liu, 1988). Thus, the low macroinvertebrate numbers recorded in the 1959 survey could reflect the very unusual hydrological conditions that applied in that year (and also in 1960 and 1961). The 1986 survey was likely conducted just prior to the closure of Longyangxia Dam, the largest dam in the headwaters (Figure 31). From 1986 to 1999 the degree of regulation increased (Figure 31), the volume of water abstracted increased (Figure 36), the incidence of cease to flow increased (Figure 44), and there was a step-reduction in flow due to climate change (Figure 34 and Figure 35). The survey of Zhao (2010) was undertaken after Xiaolangdi Dam began operation in late 1999. The policy of sediment and flow regulation (Shang et al. 2005; Xu et al. 2005) has resulted in increased baseflows, no cease-to-flow events, and an annual sediment scouring flow. The increase in macroinvertebrate taxa number noted by Zhao (2010) may provide some preliminary indication of a positive ecological response to the environmental flow regimes that have been in place since 2000, and the generally reduced TSS concentration.

High turbidity and mobile sediments are known to be primary controls on macroinvertebrate assemblages (Kaller and Hartman 2004; Vasconcelos and Melo 2008). In particular, the reported proportion of taxa number comprising molluscs in the Yellow River (6.3 per cent of invertebrate taxa) (Zhao 2010) is lower than that previously described for other similarly large rivers (c.f. 50 per cent in the Nile River (El-Shabrawy and Fishar 2009) and 21 per cent in Yangtze River (Xie et al. 1999)). As molluscs are filter feeders (Liang and Wang 1999) and are dependent on sandy substrates for habitat (Xiong et al. 2008; Hu et al. 2007), a high proportion of silt and clay-sized suspended sediment is likely to be a factor in the low numbers of molluscs observed in the middle and lower reaches of the Yellow River. Although high sediment loads are typical of the lower Yellow River, since large-scale regulation began in the 1960s, there was a shift towards a greater proportion of finer-grained material being transported, due to trapping of the coarser fraction in the dams and catchment soil conservation measures (Xu 1999; Xu 2005b; Wang et al. 2007; Xu et al. 2009). Since the late 1960s the particle size of the bed and suspended sediment become finer, but after sediment-water releases from Xiaolangdi Dam began in 2002, in the lower Yellow River the trend reversed, and the particle size became coarser (Wang H et al. 2010).

Benthic fauna require unconsolidated substrates that allow them to use interstitial spaces between particles for habitat (Duan et al. 2007). Fine-bed sediment may therefore account for the types of species recorded by Zhao (2010) in the lower reaches of the Yellow River. In contrast, macroinvertebrate diversity observed by Zhao (2010) in the middle reaches was higher than at sites in other reaches. This may be due to the fact that most of the middle reach sites surveyed by Zhao (2010) (Fugu, Wubao, Sanmenxia and Xiaolangdi) were located immediately downstream of dams, where scouring by flow releases may have given rise to coarser substrates. There is also a likelihood that improved water quality (Figure 70), including much reduced TSS (Figure 78 and Figure 79), and altered water temperature (Figure

76 and Figure 77) could have been a factor in the relatively high taxa diversity recorded by Zhao (2010) in the lower Yellow River.

Stability and diversity of substrate were identified by Zhao (2010) as primary controls of macroinvertebrate assemblages. Areas of remnant vegetation were also implicated as important habitat features for macroinvertebrate assemblages.

A relationship describing suitability of flow for rearing of Chinese shrimp in the June-August period was established on the basis of a flow-salinity relationship derived by Sun and Yang (2010). Ideal salinity is not expected for the entire rearing period because this is the traditional high flow period, when flows were regularly high enough to create freshwater conditions in the estuary. Under current flow regulation, at least one managed high flow event is released during this period. It is possible that the shrimp respond to these high flows by moving further downstream into the Bohai to find suitable salinity conditions. Given the historical frequency of suitable habitat availability, it was considered reasonable to expect that flows should be in the suitable range for at least 50 per cent of the June–August period.

Based on the discussion above the key flow-dependence of macroinvertebrates are likely to include:

- flushing flows of sufficient magnitude and appropriate timing and frequency to remove from the bed clays and very fine silts deposited during low flows
- baseflows to maintain appropriate magnitude and timing of low flows (for providing adequate area of habitat, and habitat with adequate dissolved oxygen concentrations)
- flows of appropriate magnitude, duration and timing to maintain remnant riparian vegetation
- flows to maintain sediment and salinity dynamics in the estuary.

Of these objectives, the first may not be relevant, as the data from the lower Yellow River appear to indicate that sediment (suspended and bed) has been coarsening since Xiaolangdi Dam began operation. However, whether this is the case at all locations and at all times warrants further investigation.

10.5 Aquatic macroinvertebrate flow objectives

Macroinvertebrate-based ecological objectives were identified for the lower Yellow River in relation to the maintenance of: geomorphic and hydraulic diversity; riparian, submerged and emergent aquatic vegetation; critical dissolved oxygen thresholds; and sediment and salinity dynamics in the estuary (Table 33).

Table 33. Macroinvertebrate flow objectives.

No.	Objective	Flow component	Hydrologic/hydraulic criteria	Mean annual frequency/ duration	Inter-annual frequency	Timing	Reach
M1	Prevent habitat loss through drying of shallow areas and pool crossings	Cease to flow	Q ≥ YRCC warning standards of low flow emergency	Continuous	100% of the time	All year	All reaches
M2	Maintain reasonable area of shallow habitat at pool crossings	High flow and low flow	≥ 80% of wetted area at pre-Sanmenxia median baseflow for each month	Continuous	≥ 75% of the time	Each month	All reaches
M3	Maintain submerged aquatic vegetation e.g. Vallisneria, Potomageton and Myrriophylum spp.	See vegetation objectives					
M4	Maintain aquatic emergent vegetation e.g. Phragmites and seasonally submerged meadow vegetation	See vegetation objectives					
M5	Maintain minimum 2 mg/L dissolved oxygen, particularly in deeper pools	Low flow and high flow	0.01 m/s to maintain mixing in larger riverine pools*	Continuous	≥ 75% of the time	Each month	All reaches
M6	Maintain favourable salinity at estuary and mouth for rearing of Chinese shrimp	High flows	191 ≤ Q ≤ 1227 m_3/s	≥ 50% of the time in Jun-Aug	≥ 75% of the time	June-Aug	Reach 4
M7	Maintain unconsolidated soft-bottom, substrates in estuarine backwaters and tributaries	Bankfull	Sediment load to maintain positive balance of sediment deposition over erosion in and around the estuary mouth. See geomorphology objectives.				Reach 4
M8	Maintain tidal flushing and associated salinity dynamics to support estuarine dependant species	Bankfull	Flow to scour estuary mouth and maintain adequate channel capacity for tidal flushing. See geomorphology objectives.				Reach 4

* Based on expert opinion; refinement of this criterion will require investigation.

Chapter 11. Plants and wetlands

Much of the asset value provided by birds, fish and macroinvertebrates is derived from healthy and diverse vegetation communities. In the lower Yellow River, the vegetation assets occur in three main environments: wetland and riparian, riverine lake, and delta.

11.1 Wetland and riparian environments (river channel, and Mengjin, Zhengzhou and Kaifeng wetlands)

The channel of the lower Yellow River contains three important riparian wetland assets in reach 1, between Xiaolangdi and Gaocun, namely Mengjin, Zhengzhou and Kaifeng Nature Reserves. While the river channel downstream of Gaocun (reaches 2 and 3) has largely been narrowed and stabilised into a single thread channel, with agriculture encroaching right to the edge of the channel, the channel in reach 1 retains a braided, multi-channel morphology, and channel migration is possible. Dynamism of channel morphology is conducive to the formation of and maintenance of healthy riparian wetlands. While the Mengjin, Zhengzhou and Kaifeng Nature Reserves are protected, their health is threatened by their small spatial extent, hydrological alteration, and proximity to urban areas (Zhang Z et al. 2010; Zhao et al. 2011; Xu et al. 2011).

The Mengjin, Zhengzhou and Kaifeng Nature Reserves (reach 1) were visited by the Scientific Panel for this project. While the river channel between Gaocun and Lijin (reaches 2 and 3) was not visited by the Scientific Panel, advice from YRCC, the literature, and examination of remotely sensed imagery suggested that this reach supports very little aquatic vegetation and has simplified physical habitat, with much of the channel constrained by stabilising groynes (particularly reach 3). No wetlands of national importance for birds have been identified in the reach between Gaucon and Lijin (BirdLife International 2009).

Wetlands along the lower Yellow River in Henan (Xiaolangdi to Dongbatou) have decreased markedly in area (19 per cent decrease), becoming more fragmented (21 per cent increase in number of wetland patches) between 1987 and 2002 as a consequence of human activity and natural change (Liang and Ding 2004). The total area of rice wetland increased, while the other wetland types decreased. Among those, the area of the bulrush (rushes of the genera *Scirpus* and *Typha*) wetland decreased the most. In 1987, it comprised 0.5 per cent of the total area, but in 2002, it comprised 0.11 per cent (Liang and Ding 2004). In making their estimates of wetland change (using Landsat images), Liang and Ding (2004) considered the area inside and outside of the main flood dikes. Most of the wetland area was located outside the dikes, so these areas were watered either from groundwater sources, or from irrigation runoff. Many bird species use wet rice paddies as foraging sites (Brazil 2009), although the importance of this habitat between Xiaolangdi and Gaocun is unknown.

In ancient times wetlands were widely distributed in Kaifeng City, which made the city known as 'a region of rivers and lakes' (Cao 2008). A study of wetlands in Kaifeng City by Cao (2008) found that between 1987 and 2002 the area of natural wetland (river, lake and bottomland wetland) reduced by about 45 per cent. This was explained by direct reduction of wetland area due to increasing frequency and duration of cease to flow events on the Yellow River during this period, but also because the exposure of wetlands due to drying of the river made it relatively easy for local residents to convert wetlands to farmlands.

The natural floodplain within the dike-protected river channel of reach 1 is widely developed for agriculture, particularly annual crops. Prior to operation of Xiaolangdi Dam in 2000, every year the river overflowed and submerged the whole or a significant part of the floodplain with seasonal floods. Regulation of the flow disrupted the wet-dry cycle, and typical wetland attributes have been lost (Zhao et al. 2011; Xu et al. 2011). In reach 1, riverine vegetation is restricted to a narrow zone between the most recently re-worked, and therefore bare, sediment and the normal upper limit of high summer water levels (Figure 87).

Zhang Z et al. (2010) surveyed the vegetation in Zhengzhou Huanghe Wetland Nature Reserve at 68 quadrats in April and May 2008. They found that species diversity was much higher in the wetlands areas compared to the terrestrial areas. The diversity of the plant community in the wetlands was attributed to the physical diversity of the habitats. A total of 61 species were found, belonging to 23 families and 51 genera. The plants were classified into 13 communities:

Figure 87. Recently reworked sediment surrounding a stand of immature *Tamarix chinensis* and meadow vegetation at Mengjin Wetlands.

Photo taken in spring 2010 (credit: Marcus Cooling, Ecological Associates, Adelaide)

- Scirpus planiculmi – Paspalum distichum
- Myriophyllum spicatum – Potamogeton crispus
- Gaura parviflora
- Tamarix chinensis – Conyza canadensis + Phragmites australis
- Phragmites australis
- Typha orientalis – Scirpus planiculmis
- Imperata cylindrica – Glycine soja
- Apocynum venetum – Imperata cylindrical
- Equisetum hiemale – Bidens spp
- Lamium barbatum – Equisetum hiemale
- Amorpha fruticosa – Apocynum venetum
- Alternanthera philoxeroides
- Polygonum hydropiper – Salix chaenomeloides + Typha orientalis

Of these, *Tamarix chinensis – Conyza canadensis + Phragmites australis*, *Phragmites australis* and *Typha orientalis – Scirpus planiculmis* communities had the highest species richness.

Zhang M et al. (2010) investigated the distribution of wetland vegetation in Zhengzhou Huanghe Wetland Nature Reserve on the basis of a field survey in 2008, interpretation of June 2007 SPOT5 imagery, and analysis of hydrological records. Inundation of the Zhengzhou wetlands was divided into three levels (Table 34):

- the ‘soft beach’ inundated at flows of 800–1000 m3/s
- the ‘second beach’, at 1.5 m above the soft beach, inundated at flows > 1000 m3/s
- the ‘old beach’, at 2.5–4.0 m above the second beach.

Following the *National wetland survey and monitoring procedures*, Zhang M et al. (2010) divided the wetlands of the Zhengzhou Yellow River Wetland Reserve into three categories: river wetlands, wetlands, and marshes. The marshes are herbaceous wetland and Tamarix (*Tamarix chinensis*) shrub swamps. The estimated area of river wetlands was 11,366 ha, the area of herbaceous wetland was 3043 ha, the area of Tamarix shrub was 484 ha and the area of artificial wetlands (fish ponds) was 304 ha. In total, these areas represented only 42% of the area protected by the reserve, with most of the remainder being farmland. Most of the old beach wetland has been converted to farmland and fish ponds (Zhao et al. 2011; Xu et al. 2011).

Zhang M et al. (2010) observed that although the peak and minimum annual discharge followed increasing trends over the period 2002 to 2008, the trends in peak water level and minimum water level were declining. This was due to the effectiveness of the WSDR events in scouring the channel and lowering the bed elevation. Thus, over time, the current bench levels will tend to receive less frequent inundation. Maintenance of the vegetation communities as observed by Zhang M et al. (2010) will require ongoing geomorphological adjustment (building of benches at lower levels), and migration of the plant communities to the lower elevations. This can be achieved naturally (Table 34), provided there are no artificial barriers to these processes.

Under WSDR events the soft beach is inundated, as well as part of the second beach (Table 34). The sediment of the soft beach is reworked by the WSDR event. While Zhang M et al. (2010) suggested that the soft beach would ideally be colonised by submerged aquatic macrophytes (Table 34), it is more likely that the soft beach will be bare sediment. The submerged aquatic macrophytes probably better belong in backwater areas and cut-off channels.

Table 34. The restoration zoning and restoration methods suggested by Zhang M et al. (2010) for wetlands in Zhengzhou Huanghe Wetland Nature Reserve.

Zone	Hydrological target	Plant community	Main species	Restoration method
Soft beach	Reworked by annual WDSR event	Algae and some annual herbs	*Hydrilla verticillata, Scirpus triqueter, Myriophyllum spicatum,* etc.	Natural restoration
Second beach	Brief inundation by the annual WDSR event	Low macrophytes and aquatic plants	*Polygonum hydropiper, Conyza canadensis, Inula britannica, Phragmites australis,* etc.	Natural plus active restoration
	Inundate every 3–5 years	Tall macrophytes and aquatic plants (meadow)	Polygonum lapathifolium, Conyza Canadensis, Imperata koenigii, Phragmites australis, Calamagrostis pseudophragmites,Tamarix chinensis	Active restoration
Old beach	Inundate every 6–10 years	Xerophytic plants and shrubs	*Herba Ecliptae, Conyza canadensis, Phragmites australis, Setaria glauca, Suaeda glauca, Chenopodium album, Crypsis aculeate, Imperata cylindrica, Typha angustifolia, Scripus tabernaemontani, Tamarix chinensis, Amorpha fruticosa, Salix matsudana,* etc.	Partial active restoration
	Inundate every 10–20 years	Xerophytic plants and Salix spp.	*Imperata cylindrica, Setaria glauca, Eclipta prostrata, Phragmites australis, Tamarix chinensis, Salix matsudana, Populus euramevicana,* etc.	Restoration not feasible
	No flooding in long term, reclaimed for farmland	Crops	Wheat, corn, cotton, peanuts, etc.	Restoration not feasible

Note: Natural restoration is to allow the river morphology to dynamically adjust to the changed sediment and hydrological regime, with plant colonisation following in sequence. Active restoration involves planting and artificial watering.

Observation of groundwater bores by Zhao et al. (2011) and Xu et al. (2011) at Kouma (42.4 km downstream of Xiaolangdi in the Mengjin wetland area) identified an area 200 m from the river's edge where there was a strong interaction between the river and the groundwater during the WSDR events. There was a relatively weaker interaction at distances 200–400 m from the river's edge. Zhao et al. (2011) and Xu et al. (2011) suggested formally protecting from development a 200 m wide riparian buffer, and allowing moderate cultivation to proceed in a transition zone at 200–400 m from the river's edge.

For higher level wetlands not inundated by the WSDR, Zhang M et al. (2010) recommended active restoration, using construction, revegetation and artificial watering. Much of the old beach, having long been reclaimed for farmland, was considered by Zhang M et al. (2010) and Zhou et al. (2011) to be unsuitable for restoration. The inundation frequencies suggested by Zhang M et al. (2010) should be considered the bare minimum for healthy vegetation, and are only suitable as a minimum if the roots of the plants are being wetted from below at times of lower flows (via wetting of the sandy bank material). Since regulation of the river by Xiaolangdi Dam, the water table rises to within 0.5 m of the surface only during the relatively brief WSDR events, while at other times it is much lower.

Submerged aquatic macrophytes, including *Potamogeton cripus* and *Myriophyllum spicatum* were observed by the Scientific Panel in the riverine wetlands. These plants are predominantly submerged and rely on the penetration of light into the water to grow. They therefore grow in shallow water, which would generally be less than 1 m deep. They have limited tolerance to shear stresses associated with flows. Submerged aquatic macrophytes will therefore be most common in backwaters, ox-bows and slower-moving parts of the main river channel where water is shallow (Figure 88). Submerged aquatic plants are grazed directly by fish (such as grass carp, *Ctenopharyngodon idellus*) and waterbirds (such as waterfowl). They also provide substrates for biofilms that are grazed by snails, which are an important food sources for fish and birds. Dense beds of submerged aquatic macrophytes can be used as spawning and nursery habitat for some fish species.

Figure 88. *Potamogeton crispus* in a backwater of the Yellow River at Kaifeng Wetlands.

Photo taken in spring 2010 (credit: Marcus Cooling, Ecological Associates, Adelaide)

Access to submerged aquatic macrophytes in winter is important to winter migrant birds like the grey heron (*Ardea cinerea*). The availability of ice-free open water will be related to lake extent and depth over winter.

Benthic algal biofilms were observed by the Scientific Panel to be present in shallow river water and along the damp shoreline. Biofilms contribute to the river food-web as they are grazed directly by fish or grazed by invertebrates such as snails that form prey for fish and waterbirds.

Diverse meadow communities form on floodplain areas that are subject to waterlogging or flooding by high river levels in spring, summer and autumn. The aboveground biomass of this community is strongly seasonal. It comprises perennial species which emerge in spring from dormant propagules or storage roots in the soil (e.g. *Typha angustifolia, Typha minima, Imperata cylindrica*) and annual species (e.g. *Sonchus oleraceus, Rorippa globosa*), which germinate in spring. The biomass is likely to be highest in early autumn when temperatures are high, days are long and high river levels and monsoon rainfall provides abundant soil water (Figure 89).

Figure 89. Meadow communities in spring (left) and autumn (right).

The photograph on the left is at a cut-off meander near the main dike north of Kaifeng in spring 2010 (credit: Marcus Cooling, Ecological Associates, Adelaide) The photograph on the right is at Zhengzhou wetlands in autumn of 2009 (credit: Zhao Weihua, CAS, Hydrobiology, Wuhan).

Several of the species that form the meadow community are not adapted to prolonged, deep inundation. It is likely that at lower elevations the community is dominated by emergent macrophytes such as sedges, and Typha spp. and at higher elevations it is dominated by herbs such as *Cnidium monnieri, Comnyza canadensis, Rumex crispus* and *Potentilla supina.*

Meadow vegetation contributes to the food web of the river by providing forage for herbivores such as waterfowl (ducks and geese) and fish (such as grass carp). Aquatic invertebrates grazing on vegetation and on biofilms also contribute to the food web. Flooded dense meadow vegetation will provide nesting materials and sites for waterbirds and shelter for juvenile fish from predators. Many frog species lay eggs in flooded emergent vegetation to anchor eggs against the current and provide young with access to a productive habitat.

Chinese tamarisk (also known as five-stamen tamarisk or saltcedar), *Tamarix chinensis*, and willows, *Salix* spp., grow at elevations above the normal summer flooding level (Figure 87). In favourable conditions these species grow as trees more than 6 m high (Cui et al. 2010b) but were observed on the reach 1 wetlands only as immature shrubs to a maximum of 2.5 m high (Figure 90). The data of Cui et al. (2010b) from the Yellow River delta suggest that these plants would be up to 3 years old. The lack of mature trees indicates that the trees have recently colonised the area, perhaps following a disturbance such as a severe flood or fire, or change in river course. In summer they form a shrubby over-storey that would provide forage and shelter for waterbirds and other vertebrate fauna.

Cui et al. (2010b) found that, in the delta area, *T. chinensis* individuals were mainly distributed in areas of modest water table depth and moderate soil salinity conditions. *T. chinensis* grow better in locations where groundwater is accessible, but mature individuals cannot survive in a site where long term surface water exists, as their roots may become putrefied (Cui et al. 2010b). Data from other areas suggest that when the depth to the water table exceeds between 3 and 10 m, *T. chinensis* begin to disappear, while Cui et al. (2010b) found that in the Yellow River delta, the plants were smaller when the depth to the water table was greater than 1.5 m. *T. chinensis* is a halophilic species and its seed requires a certain degree of salinity to germinate (Zhang LB et al. 2008). In the Yellow River delta, all individuals grew in locations where soil salinity was over 10 psu[28] (Cui et al. 2010b). Some ecological characteristics of *T. chinensis* such as the height and diameter had negative relationships with soil salinity. The tolerance range of *T. chinensis* to soil salinity varied from 10 to 60 psu (with younger plants less tolerant) in the Yellow River Delta (Cui et al. 2010b). Overall, Cui et al. (2010) found that sites with depth to water table less than 1.5 m and soil salinity less than 30 psu were more suitable for the growth of *T. chinensis* than sites with deep water table and high salinity.

28 psu is practical salinity unit of 1978 relative to a standard KCL solution of ocean water (PSS-78). In practice, psu is similar to parts per thousand. Standard ocean water is 35 psu. Cui et al. (2010) measured soil salinity by mixing a dry soil sample with deionized water to a standard ratio of 1:5.

Figure 90. Shrub land formed by *Tamarix chinensis* and *Salix* sp. at Kaifeng Wetlands.

Photo taken in spring 2010 (credit: Marcus Cooling, Ecological Associates, Adelaide)

Tamarix chinensis can spread both vegetatively, by adventitious roots or submerged stems, and sexually, by seeds. Thus, stands of *T. chinensis* form root networks that resist surface soil erosion and slow the downstream transfer of sediment. A long residence time for sediment will increase the opportunities for more diverse plant assemblages to establish and will contribute to habitat complexity.

Where the river abuts a floodplain surface stabilised by *T. chinensis*, undercutting by river shear forces tends to form vertical banks (Figure 91) (possibly also formed from slumping associated with rapid recession of the annual WSDR event). Exposed vertical banks are an important habitat requirement for sand martin (or bank swallow), *Riparia riparia*, and common kingfisher, *Alcedo atthis*, which may nest on the floodplain of the lower Yellow River. The resistence of *T. chinensis* to surface erosion may also increase the diversity of physical features on the floodplain such as pools and backwaters. Diverse physical features can promote biodiversity by increasing the range of physical habitats available at a site.

Mature woodlands are likely to have been an important component of floodplain vegetation in the past, but were not observed by the Scientific Panel. A number of *Salix* sp. and *T. chinensis* occur in the area and they potentially form tall woodland trees. They are an important nesting habitat for waterbirds. They also contribute woody debris which is important in river ecosystems for the physical shelter it provides for fish and the grazing substrate it provides for aquatic invertebrates. These woodlands may eventually form where immature tree species were observed. The geomorphologically dynamic nature of reach 1 would maintain a high diversity of patches of vegetation communities at different stages of succession.

11.2 Riverine lake (Dongping Hu) environment

Dongping Hu (418 km^2) is an important ecological asset in reach 3. It provides an indication of the floodplain lake habitat that historically may have been present to a greater extent. Dongping Hu is located on the right bank of the Yellow River near Xiaoqinghe in Shandong Province. The lake receives water from the Dawen and Wen rivers, which are the largest tributaries of the lower Yellow River in Shandong. Under normal conditions, water from the tributaries flows to the Yellow River via Dongping Hu, with the lake level normally held higher than the level of the Yellow River by a weir and regulating structure at the head of the lake outlet channel, about 5.6 km from the Yellow River. During high flow conditions in the Yellow River, when the river water level exceeds the height of the weir crest, flow can be reversed, from the Yellow River to Dongping Hu. In the early flood season from July to September, the water level is controlled lower than 42.0 m, reserving sufficient storage capacity for flood control. In the late flood season during October, the water level is raised to between 42.0 m and 43.0 m (Sun et al. 2007).

Figure 91. Undercut bank formed by the river shear forces, and perhaps slumping, on unconsolidated floodplain sediment, the surface of which has been stabilised by *Tamarix chinensis* (Mengjin Wetlands).

Photo taken in spring 2010 (credit: Marcus Cooling, Ecological Associates, Adelaide)

Open water is an important habitat component at Dongping Hu. Open water occurs where water is too deep to support submerged aquatic macrophyte growth. The growth of aquatic plants will usually be limited by light at depths of more than 3 m in clear water. Open water provides habitat for large fish species and habitat for deep-diving waterbirds.

Dongping Hu supports extensive beds of submerged and semi-emergent macrophytes that are likely to include *Hydrilla* sp., *Ceratophyllum* sp., *Myriophyllum* spp., *Potamogeton* spp. and *Vallisneria spiralis* (Figure 92). *V. spiralis* is a critically important food plant for waterbirds of conservation significance, including tundra swan, *Cygnus columbianus*, and swan goose, *Anser cygnoides*, which feed on carbohydrate-rich stem bases, called macrophyte tubers. The macrophyte *V. spiralis* grows in depths of up to 3 m, or shallower in turbid conditions, and requires a period of sustained flooding over spring, summer and winter to grow. Waterbirds access the tubers in shallow water or on mudflats that are exposed by falling water levels in autumn (Zhang Y et al. 2010). The leaves of submerged and semi-emergent aquatic macrophytes are grazed by waterbirds, fish (such as grass carp) and snails (Jin 1995 cited in Li 2010; Li 2006 cited in Li 2010); the plants respond to heavy grazing with increased growth rates (Li 2010).

The growth of *V. spiralis*, and its value as a food source for waterbirds, is affected by flooding. Seeds come out of dormancy and germinate from March to May when water levels are lower and more favourable for new shoots to reach the water surface (Li 2005). It grows vigorously at the onset of monsoon rains (Holm, 1997). Spring and summer water levels must be maintained to support the growing season of the plants. Water levels must recede late enough in autumn to allow waterbirds to access exposed mudflats before they become dry, hard and impenetrable (Zhang Y et al. 2010).

Reed, *Phragmites australis*, forms extensive beds at Dongping Hu (Figure 93). *P. australis* is an emergent aquatic macrophyte that typically grows up to 2.7 m and can achieve a density of approximately 340 stems/m^2 (Cui et al. 2008). The plant grows from a perennial carbohydrate-rich rhizome from which new aboveground shoots are produced each spring. Reed begins to germinate in spring. After the spring, summer and autumn growing season the shoots senesce but persist through winter as dead stems.

P. australis provides important habitat for waterbirds. The dense leaves and stems provide shelter for shy waterbirds such as reedwarbler, crake and bittern (Tscharntke 1992; Graveland 1999). Leaves and stems also provide material for nesting platforms constructed by a number of waterbird species. The flooded stems and dead and decaying stems provide a substrate for biofilms that support a range of grazing invertebrates and fish (Tscharntke 1992; Gan et al. 2010).

Figure 92. Submerged aquatic macrophyte bed at Dongping Hu.

Photo taken in spring 2010 (credit: Marcus Cooling, Ecological Associates, Adelaide)

Figure 93. *Phragmites australis* grassland at Dongping Hu.

Photo taken in spring 2010 (credit: Marcus Cooling, Ecological Associates, Adelaide)

P. australis, tolerates a sustained maximum depth of 0.75 to 1.5 m (Haslam, 1972) but will tolerate deeper water during intermittent floods. Plants grow best in seasonally fluctuating shallow water up to 0.5 m deep. In a study in the Yellow River Delta by Cui et al. (2008), *P. australis* plants achieved a maximum height of 2.7 m when growing in water depths exceeding 1.5 m, and plant density was highest at 0.2 to 0.5 m depth. At the annual average water depth of 0.3 m, both the average reed density and the coverage peaked, with density and coverage declining at shallower and deeper water depths (Cui et al. 2008). Large-scale change in the water depth was considered by Cui et al. (2008) to be deleterious to the growth of the reed.

11.3 Yellow River delta environment

The main ecological asset on the delta is the Yellow River Delta National Nature Reserve. The river is constrained within levees, which also enclose a limited floodplain area. Water is managed within bays along the river to provide habitat for aquatic plants and animals. Water can be provided artificially to delta wetlands distant from the river channel using a gravity fed system of channels connected to the river by sluice gates. However, elevation differences mean that this system can only be operated when flows exceed 3000 m^3/s, which only occurs during WSDR events (Jiang Xiaohui, YRCC, pers comm., November 2010). As an alternative, water can be pumped from the river to the delta wetlands (Cui et al. 2010). Intertidal zones also occur in embayments close to the river channel. These zones include extensive areas of sand flat, *Suaeda salsa* shrub land and *Tamarix* woodland. Vegetation cover is approximately 53.7% of the area inside the Nature Reserve, and includes the largest area of coastal vegetation in China (BirdLife International 2009).

The diversity of habitat types and extensive areas of wetlands within the Yellow River Delta wetland complex support at least 265 bird species (Chen et al. 2007). The Reserve contains 38,534 ha of intertidal flats and 32,772 ha of marshland, saltpans and fish and shrimp ponds providing critical stopover habitat for migratory waders (Barter, 2002). The Reserve provides important habitat for seven threatened bird species (national class 1 priority) (Chen et al. 2007). The region provides critical wintering habitat for a range of species, is important as a foraging site for a diverse range of migratory birds, and provides important breeding habitat for a diverse range of summer migrants and resident species. In addition to birds, the delta supports a diverse range of mammals, reptiles, amphibians and terrestrial invertebrates (Zhao and Song 1995; Xu et al. 1997; Henan Province Forestry Hall 2001). The Delta National Nature Reserve is associated with a much larger coastal bird habitat. The intertidal area exposed by the average tidal range (2 to 2.5 m) on the western side of the Bohai is 370,000 ha (Barter 2002). This region provides critical foraging habitat for migrating shorebird species.

The vegetation ecology of the delta is dominated by the supply of sediment, which creates new areas for plant colonisation, and the gradual ecological succession of these areas into a terrestrial landscape (Zhang GS et al. 2007). Newly deposited soils form saline bare land that is exposed to the sea and tides. The soils are subject to tidal inundation, marine spray and evaporative concentration of salts from the shallow marine-dominated water table. This environment is inhospitable to most macrophytic plant life and is generally bare of vegetation.

Older soils, inland from the shore, support pioneer species: the low halophytic shrub *Suaeda salsa* together with *Phragmites australis, Limonium sinensis, Scorzonera mongolica* and *Plantago depressa*. The higher elevation of these areas (1.8 m above sea level) reduces exposure to the sea. The water table is deeper, reducing the potential for evaporative concentration of salts in the soil, and also improves the flushing effects of rainfall on the soil. However, soil salinities remain high, reported as 0.5 to 0.6% salt by Zhang GS et al. (2007) and 3 per cent by Yue et al. (2002)[29].

Suaeda salsa (Linn.) Pall. is also known as *Suaeda heteroptera* Kitag; it has the common names seepweed and seablite; in China it is known as 盐地碱蓬. The optimal water regime for *Suaeda salsa* has been described as inundation once per year for less than 30 days or 30 to 180 days to a depth of -10–10 cm (Cui, 2009). It has been suggested that soluble salt concentrations in soil above 2.5 per cent in spring exceed the tolerance of *Suaeda salsa* and lead to plant death and the formation of bare mudflats (Wang et al. 2010). Flooding by freshwater was proposed as the mechanism to ameliorate the accumulation of soil salts through evaporative concentration. However, Zhao et al. (2007) note that 'ecological restoration' measures to flood areas of the Yellow River delta with fresh water and reduce salinity, also reduce the extent of halophytes including *Suaeda salsa*. The per cent area of wetland vegetation types supporting *Suaeda salsa* declined significantly between 2000 and 2005 as the area of Phragmites and open water increased (Cui et al. 2009).

Sand flats and nearby *Suaeda* shrublands are important habitat components for waterbirds. The saline delta soils are a productive source of benthic invertebrates and a food source for migratory wading birds such as the Saunders's gull, *Saundersilarus saundersi*, which feeds on the sand flat and nests in the shrublands. Swan goose is reported to feed on *Suaeda* seeds (BirdLife International 2001). The extensive open areas provide the visibility required by birds to avoid predators.

At further distances from the shoreline, *Tamarix chinensis* becomes the dominant species, with coverage of 30 to 50 per cent of the ground area, and a height of 1.3 to 1.75 m (Zhang GS et al. 2007). Species occurring with *T. chinensis* include *S. sala, P. australis, Artemisia capillaris, Imperata cylindrica* and *Metaplexis japonica*. Water table depth and soil salinity are two major factors that influence growth and distribution of *T. chinensis* (Tomar and Gupta 1985; Gries et al. 2003; Cui et al. 2010b). New trees cannot establish in areas subject to prolonged inundation. Prolonged flooding can lead to rotting of roots (Glenn and Nagler 2005). In the Yellow River delta only mature individuals are found in areas

29 These authors did not indicate the method they used to determine soil salinity, but the salinity data of Zhang GS et al. (2007) are an order of magnitude lower than expected.

subject to flooding (Cui et al. 2010b). The salinity of areas colonised by *T. chinensis* would generally be lower than that dominated by the halophyte *Suaeda salsa* (Zhang GS et al. 2007). The salinity tolerance of *T. chinensis* was reported by Chen et al. (2010) to be 10–30 psu. The salinity threshold for older individuals is higher, and they can survive in soil salinity up to 60 psu, however the height, diameter and growth of trees is reduced at salinities exceeding 30 psu (Cui et al. 2010b).

T. chinensis is a facultative phreatophyte. In the Tarim River Basin trees ideally use groundwater at depths of less than 3 m but potentially reaching the water table at 6 m deep (Zhuang et al. 2005; Fu et al. 2008). However, in the Yellow River Delta tree performance is reduced at groundwater depths exceeding 1.5 m (Cui et al. 2010b).

T. chinensis tolerates brief, intermittent flooding but is excluded from areas that are regularly flooded (Cui et al. 2010b). The water requirements of *T. chinensis* in the Yellow River Delta have been described as inundation once per year for 30 days for young trees, while mature trees can survive around 70 days of inundation (Cui et al. 2010b).

In addition to these communities, the delta supports riverine wetlands dominated by *Phragmites australis* (Figure 94). *P. australis* wetlands mainly occur in managed embayments alongside the main Yellow River channel where water distribution is controlled by a network of regulator gates (Cui et al. 2009).

Figure 94. *Phragmites australis* grassland beds in managed embayments of the Yellow River Delta Nature Reserve.

Photo taken in spring 2010 (credit: Marcus Cooling, Ecological Associates, Adelaide)

The reed community (dominated by *P. australis*) in the Yellow River Delta was observed by Cui et al. (2010b) to be replacing *T. chinensis* as a direct result of a hydrological restoration project that began in 2002. In this case, water was pumped to the area to reverse the problem of intrusion of saline water from the sea. While this action resulted in reduced soil salinity and increased biodiversity, the duration of inundation was excessive for *T. chinensis*, causing it to disappear or be replaced by *P. australis* (Cui et al. 2010b).

Ma Y et al. (2010) investigated the impact of the 2007 WSDR event on the river channel through the delta. They observed that wetland vegetation planted along the river banks enhanced channel stability. Therefore, they suggested that cropland on the riparian zone of the lower Yellow River should be replaced by wetland vegetation as a way of addressing the management goal of concentrating the flow to optimise sediment transport. Ma Y et al. (2010) also calculated that diversion of water from the river during WSDR events at a mean rate of 150 m^3/s would meet the needs of delta wetlands.

11.4 Vegetation flow objectives

Maintenance of the health and functions of the wetland ecological assets of reach 1 requires achievement of a number of objectives related to submerged aquatic vegetation, meadow vegetation and Tamarix/Salix shrubland and woodland (Table 35). These ecological objectives were interpreted in terms hydrological and hydraulic objectives (Table 35).

Reaches 2 and 3 appear to have limited riparian vegetation, due largely to the flow being confined to a rock-lined channel. Any in-channel vegetation present between Gaocun and Lijin would incidentally receive benefits from environmental flows components recommended for reach 1. From the vegetation perspective, the main ecological asset of the river between Gaocun and Lijin is Dongping Hu. Within the imposed time and resource constraints, the Scientific Panel was unable to obtain sufficiently detailed information about the way Dongping Hu is operated, and the nature of its connectivity the mainstem of the Yellow River. Any serious investigation of the environmental water requirements of Dongping Hu would require consideration of the lake's management objectives, and would need to include the lake's inflowing rivers within its scope. Thus, the Scientific Panel's objectives for Dongping Hu should be considered as preliminary and tentative. Objectives were considered for open water, submerged aquatic vegetation, and *Phragmites australis* grassland (Table 36). These ecological objectives were interpreted in terms hydrological and hydraulic objectives (Table 36).

Maintenance of the health and functions of the ecological assets of the delta (reach 4 asset) requires achievement of a number of objectives related to sand flat, *Suaeda salsa*, *Tamarix chinensis* woodland, and *Phragmites australis* grassland (Table 37). These ecological objectives were interpreted in terms hydrological and hydraulic objectives (Table 37).

The various vegetation-based ecological objectives and water requirements for the reaches were combined to a simplified set of vegetation flow objectives (Table 38). The hydraulic criteria for inundation of the various plant communities will be described in detail following hydraulic modelling of the river.

Table 35. Vegetation-based ecological objectives and water requirements for riparian wetlands in reach 1.

Habitat component	Ecological objectives	Interpreted water requirements
Submerged aquatic vegetation (*Potamogeton crispus*)	nursery habitat for fish grazing habitat for fish grazing habitat for waterfowl	slow moving or still water permanent or seasonal (July to October) inundation to less than 1 m
Meadow vegetation	nursery habitat for fish productive macroinvertebrate habitat waterbird nesting source of waterbird and fish forage and prey	3 to 6 months (June to November) of waterlogging or shallow flooding (to less than 0.3 m)
Tamarix/Salix shrubland	sediment stabilisation, contributing to habitat diversity and controlling plant community succession nesting habitat for waterbirds	9 months (June to February) of shallow groundwater 3 months (July to September) of waterlogging no flooding events longer than 1 month soil salinity 10–30 psu
Tamarix/Salix woodland	woody debris contributions to backwaters and the river channel nesting habitat for waterbirds	12 months of shallow groundwater no flooding events longer than 1 month

Table 36. Preliminary vegetation-based ecological objectives and water requirements for Dongping Hu in reach 3.

Habitat component	Ecological objectives	Interpreted water requirements
Open water	habitat for large fish habitat for deep-diving waterbirds	permanent inundation to more than 3 m
Submerged aquatic vegetation (*Vallisneria spiralis*)	nursery habitat for fish grazing habitat for fish nursery habitat for fish grazing habitat for waterfowl	slow moving or still water permanent or seasonal (July to November) inundation to less than 3 m (less in the turbid Yellow River)
Phragmites australis grassland	waterbird nesting source of waterbird and fish forage and prey	permanent waterlogging seasonally (July to November) varying inundation 0 – 0.5 m deep (1.5 m max.); optimum mean annual depth 0.3 m

Table 37. Vegetation-based ecological objectives and water requirements for the delta in reach 4.

Habitat component	Ecological objectives	Interpreted water requirements
Sand flat	feeding, loafing by wading birds	groundwater depth less than 1.8 m soil salinity greater than 30 psu
Suaeda salsa	feeding, nesting by wading birds	inundation once per year in summer for less than 30 days or 30 to 180 days of varying depth from -0.1 to +0.1 m groundwater depth 1.8 m soil salinity 5–30 psu
Tamarix chinensis woodland	diverse plant community nesting habitat for waterbirds	groundwater depth 1.5 to 3 m inundation of less than 30 days per year in summer soil salinity 10–30 psu
Phragmites australis grassland	waterbird nesting source of waterbird and fish forage and prey	permanent waterlogging seasonally varying inundation 0–0.5 m deep (1.5 m max.) in summer; optimum mean annual depth 0.3 m

Table 38. Vegetation flow objectives.

No.	Objective	Flow component	Hydraulic/hydrologic criteria	Mean annual frequency/ duration	Inter-annual frequency	Timing	Reach
V1	Maintain submerged aquatic vegetation (e.g. *Vallisneria*, *Potomageton* and *Myriophyllum* spp.)	High flow	Inundation to ≤ 1 m	Continuous	≥ 75% of the time	Jul–Oct	Reach 1
V2	Maintain meadow vegetation	High flow	Inundation to ≤ 0.3 m	50 – 100% of time	≥ 75% of the time	Jun–Nov	Reach 1
V3	Maintain *Tamarix/Salix* shrubland	High flow, low flow and low flow pulse	100% of time shallow groundwater; Jul – Sep waterlogging; inundation by summer flow pulse events ≤ 30 days; soil salinity 10 – 30 psu	Variable	≥ 75% of the time	Jun–Feb	Reach 1
V4	Maintain *Tamarix/Salix* woodland	High flow, low flow and low flow pulse	100% of time shallow groundwater (at 1.5 – 3.0 m); inundation by summer flow pulse events ≤ 30 days; soil salinity 10 – 30 psu	Variable	≥ 75% of the time	All year	Reaches 1 and 4
V5	Maintain sand flats	High flow and low flow	100% of time shallow groundwater (at ≤ 1.8 m); soil salinity ≥ 30 psu	Continuous	≥ 75% of the time	All year	Reach 4
V6	Maintain *Suaeda salsa*	High flow pulse	Inundate once per year for ≤ 30 days or 30 to 180 days of varying depth from -0.1 to +0.1 m; 100% of time shallow groundwater (at 1.8 m); soil salinity 5 – 30 psu	Variable	≥ 75% of the time	Jun–Sep	Reach 4
V7	Maintain *Phragmites australis* grassland	High flow and low flow	100% of time waterlogging; varying inundation 0 – 0.5 m deep (1.5 m max.; 0.3 m mean) in summer	Variable	≥ 75% of the time	All year	Reach 4

Chapter 12. Discussion of key issues and flow components

12.1 Flow-related issues

A number of flow-related issues have been recognised for the lower Yellow River:

- declining water availability
- sedimentation of the channel
- delta sediment balance
- reduction in extent and quality of riverine wetlands
- estuarine process alteration
- water quality limiting river health.

In the lower Yellow River, water availability is a major limitation on provision of environmental flows. The Yellow River is a working river of immense economic, social, and cultural value, so water for rehabilitation and maintenance of the river's important environmental values is scarce, and requires very careful application to maximise ecological health returns. Thus, recommendations for environmental flows in the lower Yellow River are based on the premise that the future river health will not resemble a state that existed prior to water resources development. Rather, the challenge of environmental flows assessment on the lower Yellow River is for YRCC to consider a number of options, each one requiring a different volume of water to implement, and each one likely to give rise to a particular degree (or state) of river health. These options can then be traded off against the other non-environmental demands, which also provide a range of societal benefits. This objectives report did not propose environmental flow options; rather, the needs of the assets were assessed assuming only unalterable physical constraints (such as presence of dikes and dams), and assuming the objective was a high level of stream health at low risk. The environmental flow options were developed in a companion recommendations report.

Progressive sedimentation of the lower Yellow River channel has been interrupted since Xiaolangdi Dam became operational. The annual release of water-sediment discharge regulation (WSDR) events has measurably increased channel capacity. So, for the time being, this problem has been ameliorated. While Xiaolangdi Dam has much improved control over river flows, the reservoir traps a good deal of incoming sediment, starving the river downstream. In addition, sediment delivery from the upper and middle reaches of the river has been in decline since the late-1960s due to soil conservation practices, declining catchment discharge, and dam construction. Much of the sediment delivered to the delta in recent years has been sourced from the channel downstream of Xiaolangdi Dam, as intended. One consequence of this is that the current sediment load to the delta is similar to the low level typical of 3000 years ago, whereas the current delta's characteristic of rapid growth (which significantly contributes to its high conservation value) was a product of sediment loads an order of magnitude higher than this (as prevailed from when the delta began development in 1855 until the early-1980s). Thus, maintaining the ecological character of the delta is not simply a flow issue, but a sediment issue. Even though sediment supply has been elevated above 'pristine' levels since it began its development, maintaining the delta is a conservation priority because wetland habitat elsewhere in the Yellow River (including the delta) has been lost to a vastly greater extent than the area that has been created through delta growth. Bird populations that formerly used habitat on the river or associated wetlands now rely largely on the delta. There are three possible scenarios for delta sediment balance:

1. **Rate of freshwater sediment supply = rate of delta marine erosion**

   Under this regime, the extent of *Suaeda salsa* saltmarsh community will be maintained, but the extent of mudflats will be reduced to an annually variable steady state that grows when sediment is supplied and then retreats back to the *Suaeda*. The effects would be:

   - a small extent of mudflat
   - mudflats that do not last for more than one year, so do not develop complex microbial and interstitial fauna communities
   - new areas are not colonised by *Suaeda*. The existing *Suaeda* will gradually colonised by terrestrial species and lose its distinctive species composition and structure on which some birds depend.

2. **Rate of freshwater sediment supply < rate of delta marine erosion**

   Under this regime, a small area of new mudflat created in association with the WSDR would be removed before a significant sediment load is delivered in the following year. In the meantime, older mudflat or Suaeda would be eroded. If delta growth occurs near the mouth of the Yellow River, but marine erosion of the delta occurs distant from the mouth, then for a while at least, ongoing mudflat habitat and plant succession would continue. It is not known how long this situation would be sustainable. Ultimately, the effect would be:

   - net loss of delta wetland habitat, increasing the threat of habitat loss to birds
   - trending change that may be contrary to Ramsar and possibly other wetland policy objectives.

3. **Rate of freshwater sediment supply > rate of delta marine erosion**

   This regime would create new areas of mudflat over time. Even at a low rate of growth, the effect would be:

   - new areas of mudflat gradually colonised by meiofauna (small benthic invertebrates that live in both marine and fresh water environments) that provides food resource for birds
   - maintenance of bird community and vegetation structure.

Considering the consequences of these three scenarios, it is obviously preferable to maintain a prograding delta (scenario 3 above), even if the delta is eroding in other areas. This will require coordinated management of river sediment load, sediment concentration and discharge.

Riverine wetlands have been in decline in the lower Yellow River since construction of protective dikes began some 1500 years ago. From the late-1950s to the 1980s much of the river underwent fortification with rock beaching, groynes and raising of dikes. The objective of this work is to train the river into a single stable thread, which is much easier to manage, and more efficient in transporting sediment. The reach upstream of Gaocun is the only section of the lower Yellow River that retains a truly dynamic channel. Not surprisingly, this is the only section of river where significant riverine wetlands can be found. These wetlands (Kaifeng, Zhengzhou and Mengjin), which are recognised for their high ecological values, are potentially threatened by plans to continue extending river training works into this reach. At the same time, these riverine wetlands are being threatened by encroachment of agriculture. The third major threat to the health of these wetlands is inadequate water from the river, which can be at least partly addressed through environmental flows. However, the majority of the former wetlands lie beyond the reach of the annual WSDR event, so environmental flows can benefit only narrow low-lying beach areas close to the river.

In the 1980s and the 1990s the Yellow River estuary experienced lengthy periods of time with very low freshwater inflows. This situation was immediately corrected with the operation of Xiaolangdi Dam through release of minimum baseflows, and over time baseflow releases have been further increased. Flows remain lower than they were prior to regulation, so the salinity and temperature gradients are significantly different to the ideal that would maximise productivity and utilisation by fish, and soil salinisation impacts vegetation. Nevertheless, environmental flows have potential to improve the health of the estuary.

Water quality is a significant limiting factor in the health of the lower Yellow River. While modest flow allocations can be used to dilute pollutants to an acceptable grade for non-environmental uses of the river, this grade is well below the standard required for a high level of river health. Source control, rather than increased dilution flows, is the key long-term water quality management strategy.

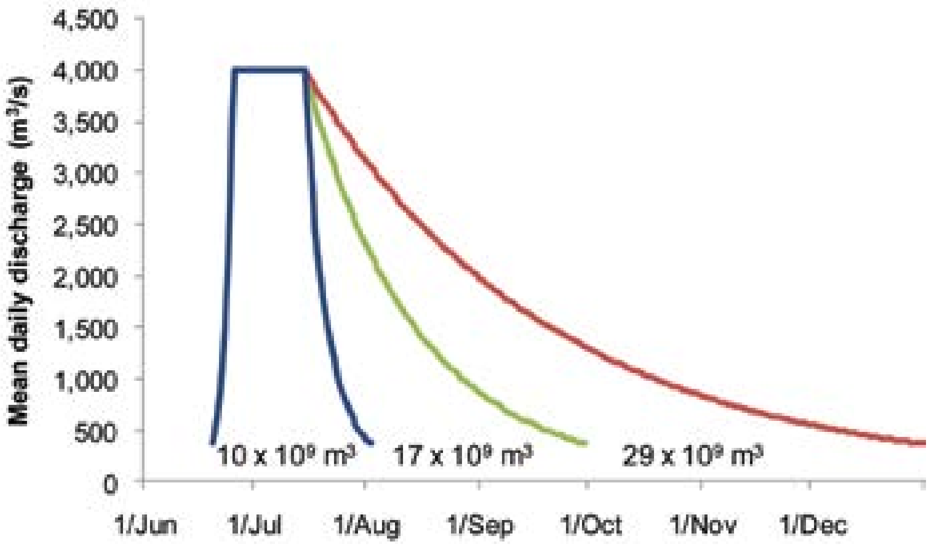
12.2 Flow components

Of the potential flow components that comprise a river flow regime (Table 16), baseflows, cease to flow (i.e. prevention of), bankfull flow, and high-flow recession were identified as being critical for the health of the lower Yellow River. Flow pulses were relevant to only a few objectives, and overbank flows were considered imprudent in this river due to high socio-economic cost and risk to human life. The low-flow period can be adequately managed by providing appropriate baseflows, but the summer/autumn high flow period is more problematic.

The high-flow period water-sediment discharge regulation WSDR event is entirely artificial, being released from Xiaolangdi Dam (although tributaries downstream of the dam can also make modest flood contributions to the Yellow River). The WSDR event has positive benefits for channel morphology, lowered flood risk, inundation of the edge of the remaining riverine wetlands, watering the delta wetlands and generating favourable salinity conditions in the estuary. For operational reasons it is preferable to make the release from late-June, which is perhaps a month earlier than the main flood period under pre-dam conditions. This does not create a major problem for the biota, but the water is 1–2 °C colder than pre-dam flows at this time of year, which could disadvantage some temperature-sensitive fish species which rely on the high flows for spawning.

The high flow period flood peak is now of a short duration compared to the pre-dam situation. For waterbirds this may not present a major problem, but for plants, consequences are likely. The areas inundated by the brief flood peaks comprise flood-tolerant woodland species (*Tamarix* and *Salix*) with an understorey of disturbance-adapted terrestrial grasses and herbs. Aquatic plants only occur in the areas subject to more sustained seasonal inundation, below about 300–400 m^3/s in reach 1 from Xiaolangdi to Gaocun. This means that the overall area of floodplain vegetation is reduced to lower floodplain terraces, and vegetation structure is therefore simplified. This issue could be resolved by extending the duration of the flood recession. For example, prior to Sanmenxia Dam, flow events initiated in summer exceeded 1000 m^3/s for more than 100 days in more than half of years (Figure 45). However, implementing an extended flood recession would require a volume of water (Figure 95) that exceeds the traditional high flow period allocation of 15 × 10^9 m^3 (recently reduced to 13.5–18.5 × 10^9 m^3), and it would drain water from the reservoir that would otherwise be later delivered for irrigation and other consumptive uses.

Figure 95. Three simulated flood events beginning on 20 June with 20 days at 4,000 m^3/s, showing total water used, (i) 43 days with maximum recommended rates of rise and fall, (ii) 102 days with recession to end of September, and (iii) 194 days with recession to end of December.



The current practice of rapid recession of the summer flood event probably has negative consequences for waterbirds. Gradually exposed vegetation and mudflats in summer and autumn (June to November) would be the principal reason that waterbirds use the riverine wetlands. In wetlands that are well connected to the river, their level changes with that of the river, in which case extended flood recession would be important for waterbirds. For wetlands that pond water behind sills, the recession of the river flood is not such an important issue. Little is known about the detailed hydraulics of the riverine wetlands in reach 1 so this issue cannot be fully resolved here. In any case, for waterbirds, flow pulses or multiple flood peaks over summer and autumn are not a substitute for a long continuous flood recession, as they do not create the conditions of gradual exposure of mudflats.

There is a suggestion that the rapid recession of the WSDR event presents a risk to bank stability, especially in reach 1. The process is one of slumping of saturated bank material when the water table does not lower through draining at the same rate as the fall in the river level. A longer, more gradual recession would reduce the risk of this form of bank instability.

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Ecohydraulic Modelling and Flow Recommendations

Executive Summary

The Yellow River study is one of three pilot sub-projects undertaken for the River Health and Environmental Flow in China Project. The Yellow River sub-project includes both a river health assessment and an environmental flows assessment. This report is one of two that cover the environmental flow assessment component. The other report provided the scientific knowledge base for the environmental flows assessment, and set the flow objectives. This report details the hydraulic analysis, documents the recommended flow options, and tests the compliance of the options over the historical period (since 1950).

Both one- and two-dimensional hydraulic models were used to establish the relationships between flow magnitude and availability of physical habitat. The 2-D models were established for three sites along the river, while the 1-D model was developed for the entire length of the river.

Following the hydraulic analysis, the environmental flow objectives (for water quality, geomorphology, fish, birds, macroinvertebrates and vegetation) were rationalised into a smaller set that satisfied multiple objectives.

The rationalised flow objectives gave rise to two environmental flow options for the river. One would present a low-risk to achievement of good river health, and the other a medium-risk. The flow options were constrained by certain operational requirements that were considered unalterable (in the short-term). The main constraint was the need to keep flow within the confines of the main channel, due to the risk to human life and socio-economic values that floods would present.

The current environmental flow practice is not dissimilar to the low-risk environmental flow regime recommended here. For this reason, compliance with the flow regime has been fairly high in recent years.

While the hydrological conditions have improved significantly since Xiaolangdi dam began operation, river health could benefit greatly from improved water quality and better access to freshwater riverine wetland and backwater environments. In the lower Yellow River, riverine wetlands can now be found only in limited areas of the reach from Mengjin to Gaoocun, and they are shrinking in area due to appropriation of floodplain land for agriculture and aquaculture. If maintained in good condition, these areas provide important waterbird habitat that complements that found in the Yellow River Delta. The health of the Delta relies on annual inflows of water from the river, but also on annual renewal of the mudflats though delivery of an adequate load of sediment from the river. At present, growth of the Delta is barely sufficient to compensate for the area lost through marine erosion.

Introduction

Background to this study

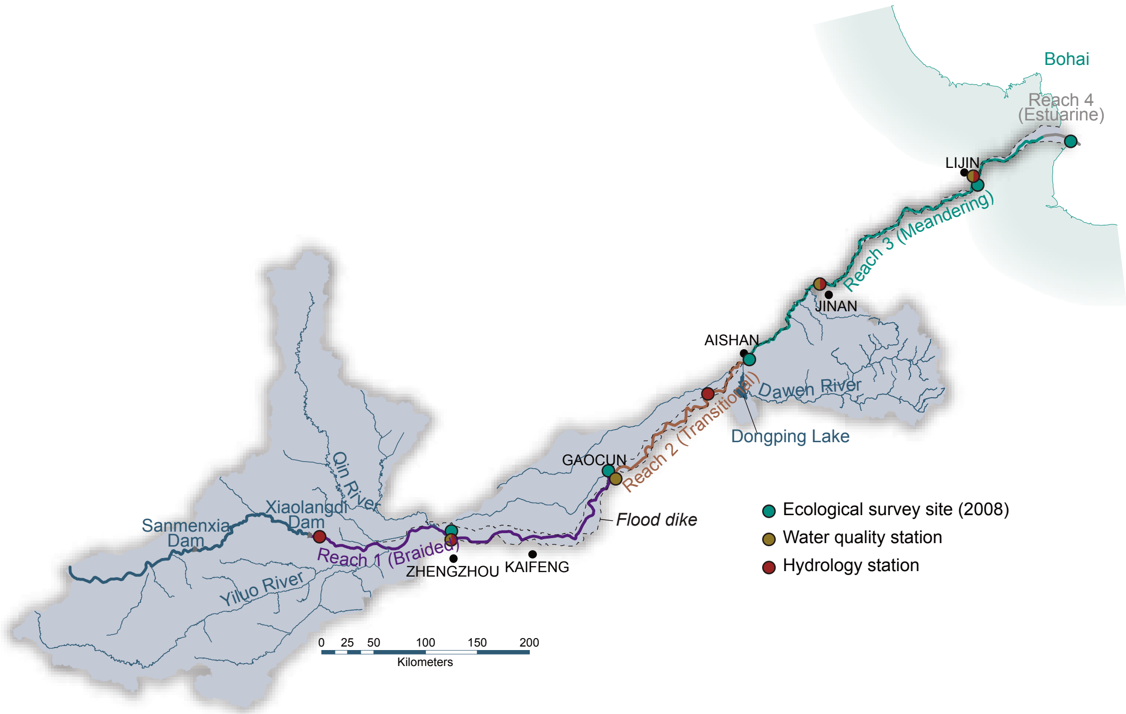
This report is a component of the Australia China Environment Development Program (ACEDP) River Health and Environmental Flow in China Project, undertaken by the International Water Centre. The ACEDP is a five-year, Australian Government, AusAID initiative with the objective of supporting and improving policy development in China in the area of environmental protection and natural resources management. This project will support those goals by strengthening China's approaches to assessing and monitoring river health, and assessing the river flows required for achieving ecological health.

The Yellow River study is one of three pilot sub-projects undertaken for the River Health and Environmental Flow in China Project. The Yellow River sub-project includes both a river health assessment and an environmental flows assessment. The main objective of the work is to trial and document approaches to river health assessment and environmental flows assessment that are applicable to the lower Yellow River specifically, and which also have potential for wider application in China.

Environmental flow assessment method

The method of environmental flows assessment used here is based on the framework proposed by Gippel and Speed (2010). This flow recommendations report is intended to be read together with Gippel et al. (2012), which set out the rationale for selecting sites and reaches, identified the flow-dependent assets, explored the flow-related issues, and set the flow objectives.Essentially, Gippel et al. (2012) provided the scientific foundation, or knowledge base, for the development of environmental flow recommendations for the lower Yellow River. For the purposes of the environmental flow assessment, the river was divided into four reaches on the basis of geomorphological characteristics. Each reach had flow and water quality data available (Figure 1).

Figure 1. Lower Yellow River, showing four reaches used in environmental flow assessment, and location of gauging stations used for water quality and hydrological analysis.



The method used here does not result in the recommendation of a single environmental flow regime that is considered "ideal" for the environment. Rather, the method derives a range of environmental flow options, each having different implications for meeting river health objectives and utilitarian objectives. Balancing the flow needs of different users is undertaken by managers, together with other stakeholders as appropriate, using the science-based information provided by the environmental flows assessment. This is the process that ultimately decides the environmental flow regime that will be implemented in a river.

Gippel et al. (2012) acknowledged, and reviewed, a long history of environmental flow assessment work in the lower Yellow River. This work was inspired by a general recognition that while the demand for water for consumptive use was increasing, and the risk to flooding posed by sedimentation of the river remained significant, the ecological health of the river was less than considered desirable. Following the construction of Xiaolangdi dam in 1999, the Yellow River Conservancy Commission (YRCC) began to implement an objective-based environmental flow regime that was integrated with the utilitarian uses of the river. From that time onwards, the YRCC has adaptively managed environmental flows, within the constraints of water availability and other considerations. While this report makes some recommendations for environmental flows, it is recognised that these are simply refinements of an existing regime.

The main contributions of the ACEDP project were: (i) to document the previous lower Yellow River environmental flows work in a structured way, (ii) to investigate the effectiveness of environmental flows to date, (iii) to further investigate the links between flow and ecology on the lower Yellow River, (iv) to transfer environmental flow technologies through application of a holistic approach to environmental flow assessment, and (v) to provide improved scientific support for the potential benefits of environmental flows, so that management decisions can be made with greater confidence.

Objectives of this report

The specification of flow components, particularly their magnitude, relies heavily on relationships between river hydraulics and river discharge. The hydraulic relationships are derived through modelling based on river morphology. One objective of this report is to describe the ecohydraulic models.

Environmental flow regimes are developed on the basis of a number of considerations, with ecohydraulics being a key one. The second objective of this report is to consider all of the relevant information and then suggest appropriate flow regime options. The recommendations build on the existing environmental flow practice in the lower Yellow River. Finally, the report highlights the main factors that constrain implementation of environmental flows in the lower Yellow River. Some of these constraints are practical (to do with limited water availability or conflicting management objectives) while some are due to knowledge gaps.

Modelling Ecohydraulic Habitat Availability

Basic concepts

The link between river hydraulics and river health

Ecohydraulic modelling is mainly concerned with relating the physical attributes of flowing water to biological, chemical and sediment transport processes.Hydraulic attributes describe the environmental conditions in a river in terms of water depth, width, velocity and bed shear stress. Knowing the preferences and/or tolerance of biota to these attributes, recommendations can be made concerning the hydrological regime that will provide the appropriate hydraulic conditions for maintaining important ecological assets. This ecohydraulic approach is based partly on ecological niche theory, where the dimensions of the niche are environmental conditions that define the range in which a species can persist. As a result of interactions with other organisms, species are often forced to occupy a niche that is narrower than their potential niche.

The IFIM (Instream Flow Incremental Methodology) approach to setting environmental flows (http://www.fort.usgs.gov/products/software/ifim/, Bovee, 1982), is based around niche theory. In this approach, preference curves are derived for each species of interest, either through empirical observations of the hydraulic environments where the species are found, or through experimentation (e.g. Edwards and Twomey, 1982; Conklin et al., 1996; Waddle, 2001). Then, the range of discharge that can be tolerated, or the discharge that maximises the area of habitat available, can be identified. In its simplest form, this approach aims to optimise the availability of habitat area for the main species of interest. Stewardson and Gippel (2003) developed the Flow Events Method to supplement the ecohydraulic approach, in recognition that environmental disturbance was an important determinant of community structure. A flow event might be considered a discrete period of time during which the flow conditions influence an ecological or geomorphological process. These events can represent conditions that are favourable to certain species, or guilds (species that exploit the same resources, often in related ways), conditions that produce an undesirable negative effect on certain species or guilds, or conditions that act to temporarily disturb aquatic communities so as to enhance habitat heterogeneity and maintain overall biodiversity. The ecohydraulic approach focuses on availability of hydraulic conditions defined in terms of tolerable or preferred depth and velocity, combined with critical temperature, substrate, cover and water quality requirements. Bed shear stress is often used to define sediment transport processes (which have ecological relevance).

The objective of environmental flow assessment is not to maximise the availability of ideal niche conditions for a limited range of key species, because favouring certain species could be at the exclusion of other species, which could reduce biodiversity. Natural river environments that rate highly in terms of river health indicators usually contain a wide range of physical form, so at any particular discharge many niches are present; this helps to explain the high biodiversity of such streams. So, the objective of environmental flows is to provide an area of tolerable or preferable hydraulic habitat conditions at the right time of the year, sufficient that the species or guilds of interest are self-sustaining. In this sense, the “species or guilds of interest” represent the ecological assets, which for the lower Yellow River intentionally covered a wide range (thus representing a wide range of niche conditions). Guidance for defining the regime of hydraulic conditions is often obtained through examination of the pattern of availability of hydraulic habitat under unimpaired, or natural, flow conditions, or when the ecological communities were known to be in a healthy state. Important hydraulic disturbance events can be characterised in the same way. The important flow events for maintaining the environmental assets of the lower Yellow River were formulated in Gippel et al. (2012). Each event was related to one or more flow objectives, and was described in terms of hydraulic requirements (if data were available) and hydrologic requirements. Some of these specifications were tentative due to lack of, or uncertain, flow-ecology information.

The role of ecohydraulic modelling in formulating environmental flow recommendations

The process of deriving environmental flow recommendations does not usually rely exclusively on data from ecohydraulic modelling of habitat preferences, because the knowledge base necessary for this approach is nearly always far from complete (which is the case for the lower Yellow River). The results of hydraulic modelling are but one input to the process followed by the Scientific Panel charged with formulating the flow recommendations.

Where suitable information linking ecohydraulics and ecology are lacking, the recommendations may be shaped by reference to the characteristics of the hydrological regime under unimpaired conditions, or at a previous time when the ecological health of the river was known to be at a level that would satisfy the current target. The hydrology of the lower Yellow river was characterised for this purpose in Gippel et al. (2012).

In highly regulated rivers like the lower Yellow River, environmental flow recommendations are also partly shaped by what are considered unalterable (in the short-term) constraints imposed by operation of the river system to meet non-ecological human needs, such as irrigation, domestic and industrial water supply, flood protection, navigation, and power generation. Some non-ecological human needs are negotiable, and might be traded against ecological benefits (in the belief that such ecological benefits might provide a valuable human benefit). In the long-term, the short-term unalterable constraints might be adjustable, but for the purpose of an environmental flow assessment they are considered fixed. The review of Gippel et al. (2012) characterised the factors that constrain environmental flows on the lower Yellow River.

Types of hydraulic model

Two types of hydraulic model are usually used in environmental flow assessment. The simplest is the one dimensional (1-D) model, while some studies use two dimensional (2-D) models. In this context, “dimension” refers to the vertical, lateral and longitudinal dimensions of the river channel and floodplain. A 1-D model predicts the mean water surface elevation (and thus depth) along a modelled reach, and the mean velocity at cross-sections along the reach, but it does not provide any detail about how velocity or water surface elevation is distributed throughout the cross-sections. The 1-D model is usually applied to partitioned cross-sections (usually left and right floodplain areas, and channel area) to give some indication of lateral variation in hydraulic conditions. A 2-D model predicts the variation in water surface elevation, water depth, flow direction, and mean velocity in the vertical over an area of river. Thus, the 2-D model describes the hydraulics for the lateral and longitudinal dimensions, but no information is provided about how velocity varies with depth.

One dimensional hydraulic models are more commonly applied in routine environmental flow assessments than are 2-D models. The reason is that 1-D models require only a series of cross-sections to be surveyed along the length of the river and the data processing is relatively routine, while 2-D models require survey sufficient to develop a detailed digital terrain model (DTM) and the data processing is more specialised. Thus, 1-D models can be relatively inexpensively applied to fairly long reaches, while 2-D models are relatively expensive and are usually limited to a short reach of river. In certain situations the advantages of 2-D models over 1-D models in characterising the hydraulic habitat outweigh their cost disadvantage. Such a situation might be where the available suitable habitat is confined to limited areas of the river cross-section, or in a river with a large spatial variation in hydraulic conditions. In these situations the mean cross-section velocity, as provided by a 1-D model, is a poor, and potentially misleading, representation of the actual habitat availability. In general, 1-D models are adequate for small streams and streams with simple and homogeneous physical form, while large rivers with variable physical form, or particular locations on rivers that are known to have high ecological importance (e.g. spawning sites) might warrant a 2-D modelling approach.

Resolution of the vertical dimension can be achieved with a 3-D hydraulic model, but such models are not usually applied in environmental flow assessments because of the high cost and technical difficulty involved.

Modelling the ecohydraulics of the lower Yellow River

1-D model

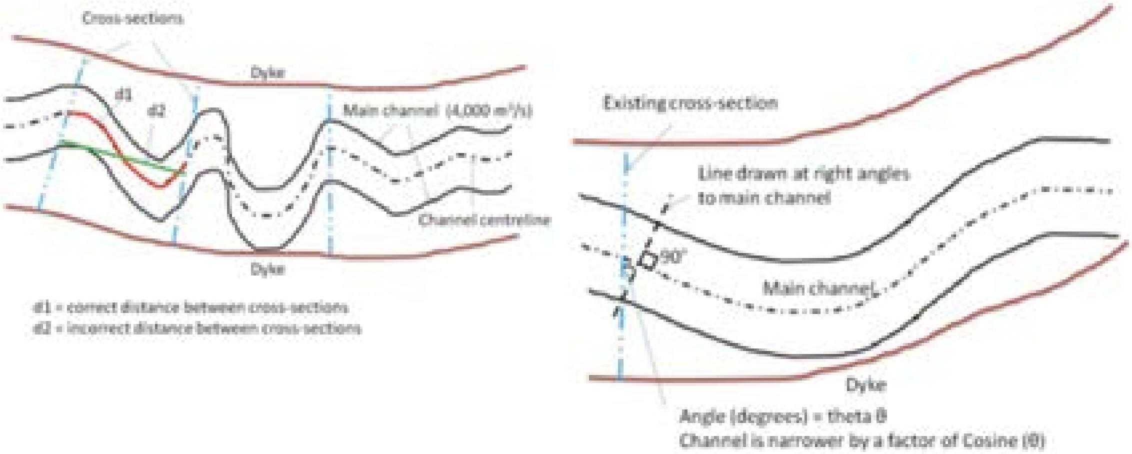
Both 1-D and 2-D hydraulic models were applied to the lower Yellow River. The 1-D model was applied because it was desirable to characterise hydraulic conditions along the entire length of the river channel, as the channel itself was identified as an important ecological asset (Gippel et al., 2012). Also, development of the 1-D model was facilitated by the ready availability of cross-section data through the annual river survey program. This survey comprises 370 monumented transects across the river, beginning at Xī xiá yuàn (at 16.91 river km, or distance downstream of Xiaolangdi) and ending at Chà #3 (at 849.13 river km). For the 1-D model, 365 of these transects were used, beginning at Dōng xiá yuàn (at 16.91 river km) and ending at Chà #3. The data from the 2010 river survey were used in the 1-D model.

The transect locations for the annual river survey were established some time ago, and they generally run perpendicular to the macro-scale river (between the outer flood dikes). The ecohydraulic habitat modelling was limited to flows less than 4000 m^3/s as this corresponds to the maximum channel capacity of the river, and it thus represents the upper limit of flows released from Xiaolangdi dam. Flows of 4000 m^3/s are contained within the main channel, so are well inside the outer flood dikes. Thus, for most transects, their bearing was not perpendicular to the downstream bearing of the main river channel, and in some locations the relative difference in bearing would change over time due to the channel shifting its course. For 1-D hydraulic modelling, transects must be perpendicular to the channel, otherwise the model interprets the river to be wider than it is in reality, and produces an erroneously low estimate of water level. The transect chainages (distance across the channel) were corrected using a simple algorithm, and the channel lengths were based on distance along the main channel centreline (Figure 2).

The HEC-RAS 1-D hydraulic model was used in the lower Yellow River study. HEC-RAS was developed for the U.S. Army Corps of Engineers. It is available for download (http://www.hec.usace.army.mil/SOFTWARE/hec-ras/) and can be used by individuals outside of the Corps of Engineers without charge. Measured Manning n values were available for some cross-sections. At other sections the Mannings n was adjusted to calibrate the result against recorded water levels at hydrologic stations.

The model was run for discharges 50, 100, 200, 300, 400, 500, 1,000, 1,500, 2,000, 3,000 and 4,000 m^3/s, producing output for water surface slope, water elevation, bed shear stress, wetted perimeter, and mean cross-section velocity (Figure 3). Values of these parameters at non-modelled discharges were interpolated using the predictions made at the modelled discharges.

Figure 2. Schematic explaining method of adjustment of channel transect data.



The 1-D hydraulic model produced results that were consistent with the understanding of the river gleaned from the review of literature by Gippel et al. (2012). Compared to the other reaches downstream, Reach 1 from Xiaolangdi to Gaocun was more variable in terms of slope, wetted perimeter (similar to width), bed shear stress and mean channel velocity, and the absolute values of these attributes tended to be higher in this reach (Figure 3). Apart from water surface slope, the hydraulic attributes had significantly higher absolute values at 4,000 m^3/s compared to 50 m^3/s (Figure 3).

Example application of 1-D model – Inundation of Mengjin wetland habitats

The 1-D model characterised the hydraulics of the entire lower Yellow River, so it could be applied to ecological assets in any location. Mengjin wetlands in Reach 1 are an important ecological asset for the lower Yellow River (Gippel et al., 2012). The area consists of aquatic, meadow, and Tamarisk vegetation communities sitated at progressively higher elevations. Although the Scientific Panel for this project did not conduct a detailed investigation of the area, some information on vegetation distribution was available in the literature. Also, a number of monumented cross-sections are surveyed in this area annually. One such cross-section is located at Xià gŭ jiē (下古街), which is 32.27 km from Xioalangdi. Cross-section survey data were available for 2002 and 2010 at this location (Figure 4).

The 1-D hydraulic model provided a prediction of the water surface elevation at Xià gŭ jiē for a range of discharges. Under 2010 conditions, at channel capacity discharge (4,000 m^3/s) for the lower Yellow River, at this location the water surface is well below the bank level (Figure 4). However, it is apparent that the cross-section has scoured considerably since 2002, in response to the annual WSDR (Water Sediment Discharge Regulation) events. Here, about half of the bed width has scoured by around 4 m (Figure 4). This change in channel form has led to a lowering of the water level for the discharge of 4,000 m^3/s by about 2.6 m compared to the situation in 2002. Thus, prior to regulation by Xiaolangdi dam, flows of this magnitude almost inundated the floodplain, and groundwater recharge would have resulted in saturated or near saturated soil conditions in the Mengjin wetlands. Since 2000, drying caused by changes to the hydrology of the river and morphology of the channel provided the opportunity for development of former wetlands into farms and fishponds (Zhang et al., 2010; Zhao et al., 2011). Together, these changes have constrained the area of natural wetland that can benefit from environmental flows. However, the 1-D hydraulic model was useful in identifying the flows that will inundate the riparian land to enhance ecological values.

Figure 3. Downstream predicted hydraulic characteristics of the lower Yellow River for the lowest and highest modelled discharges. Water surface slope is the 3-point moving average. The length of the river is divided into the four reaches that were used in the environmental flow assessment.

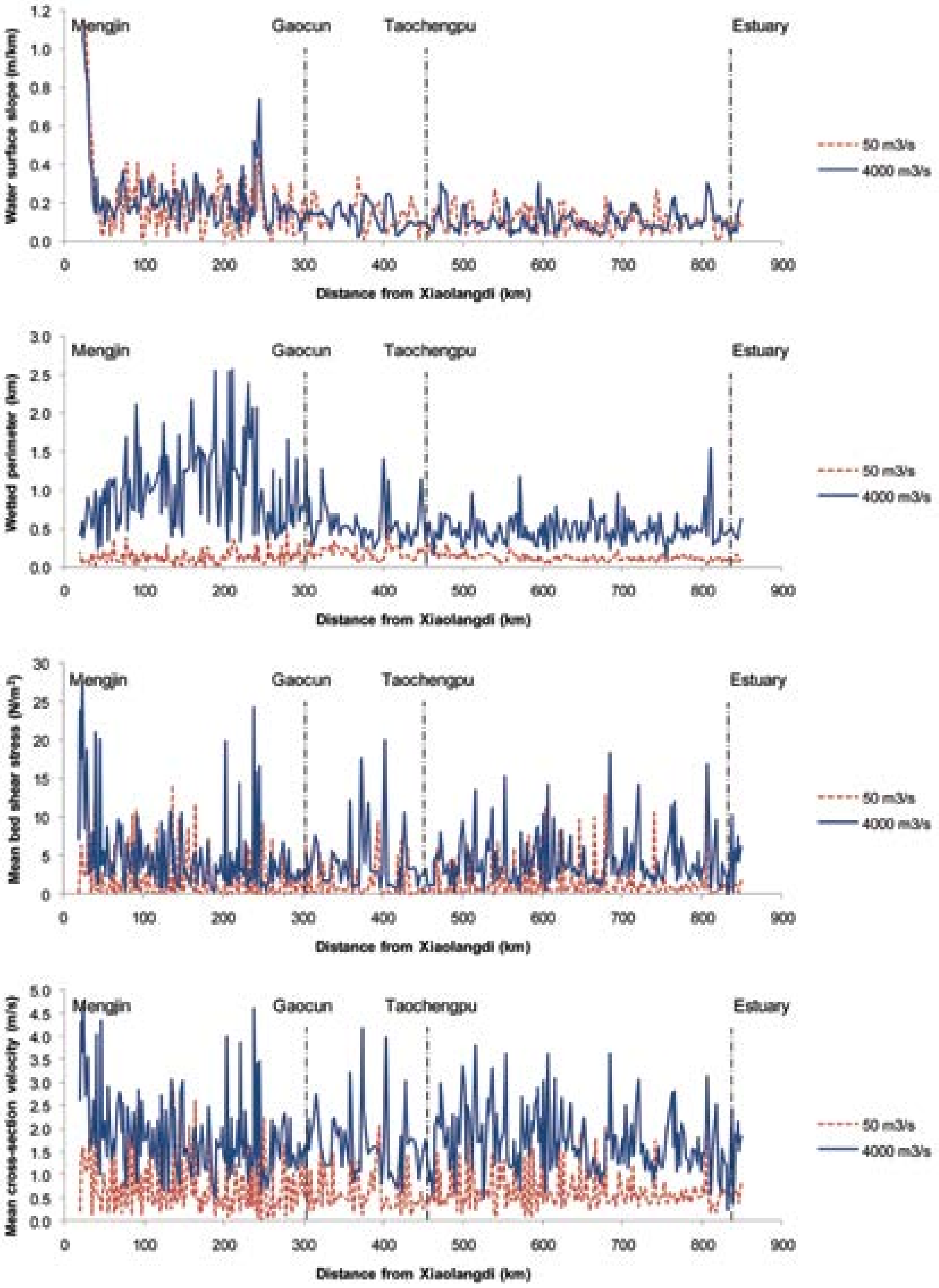
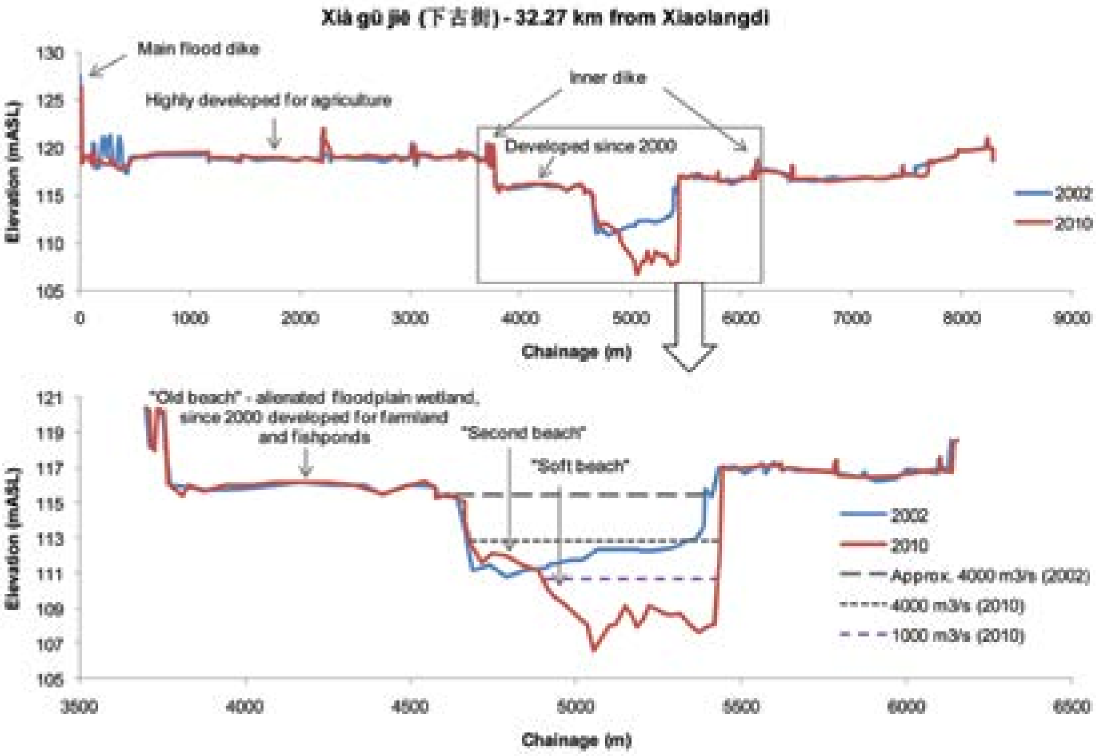


Figure 4. Comparison of 2002 and 2010 cross-section survey data at Xià gŭ jiē (下古街), in the Mengjin Wetland area, 32.27 km from Xioalangdi. The environment in this area is described by Zhang et al. (2010) and Zhao et al. (2011).



2-D model

The two-dimensional modelling for the lower Yellow River was undertaken using River2D. River2D is a 2-D depth averaged finite element hydrodynamic model that has been customized for fish habitat evaluation studies. The model was developed by the University of Alberta and is available for download free of charge (http://www.river2d.ualberta.ca/index.htm). Application of the model requires high quality bathymetric data. These data were obtained by hydrographic survey at three sites on the lower Yellow River:

- Yiluo (the junction of the Yiluohe and Yellow rivers, at 71.17 river km)
- Huayuankou (at 130 river km)
- Lijin (at 755 river km)

Each of the surveys covered a large area, because the river channel is hundreds of metres wide at these locations. Yiluo was selected because it was known as a formerly important fish spawning area. Huayuankou was formerly an important area for fish productivity, while the Lijin area is close to the estuary and would be important for any migratory species.

The model was run for discharges 50, 100, 200, 300, 400, 500, 1,000, 900, 1,200, 1,600, 2,400, 3,600 and 4,000 m^3/s. For each discharge, predictions were made of the area satisfying a range of depth and velocity criteria. The ranges were 0 – 2 m depth and 0 – 2 m/s velocity, which covered the documented range of hydraulic preferences of biota in the lower Yellow River. Output was produced for 15 increments of depth and 15 increments of velocity. Thus, for each site, predictions of available area were made for 3,150 combinations of discharge, velocity and depth. Values of available area at non-modelled combinations of discharge, velocity and depth were interpolated using the predictions made at the modelled combinations.

Example application of 2-D model – Yellow River carp habitat availability

The 2-D model was used to predict the habitat area available as a function of discharge for certain ecological criteria. For example, the hydraulic preferences of Yellow River carp for three life stages were taken from the literature (Table 1), and the 2-D model was used to predict the area of each habitat type that was available across the discharge range 0 – 4,000 m^3/s (Figure 5, Figure 6 and Figure 7). For each life stage, the area of habitat available peaked at a certain discharge. At this discharge the potential area of suitable habitat was assumed to be maximised, so that at any other discharge the available area of habitat could be expressed as a proportion of the maximum, to give a daily habitat availability index value of 0 – 1. Some life cycle stages are relevant to the entire year (adult survival, juvenile rearing) while others are relevant only to a certain season (spawning) (Table 1). The annual habitat availability was expressed as the sum of the daily index values divided by the number of days of the year that the life cycle stage was relevant. This gave a habitat availability index value of 0 – 1. An annual index value of 1 implies that on every day of the year the maximum potential area of tolerable hydraulic habitat was available; an index value of 0 implies that no suitable hydraulic habitat was available. The purpose of generating this time series of annual habitat availability was to compare the change in hydraulic habitat conditions through time with the historical (anecdotal) trend in river health reported in the literature, and to evaluate the suitability of environmental flows implemented since 2000 (see Gippel et al., 2012). The daily discharge time series from Xiaolangdi was applied to habitat data from Yiluo, while the other two sites had gauging stations located nearby. The Xiaolangdi time series had missing data for the period 1998 – 2000 (inclusive). This period was in-filled using a regression relationship between data from Xiaolangdi and Huayuankou gauges over the period 1990 – 1997. The discharge data from these two gauges were highly correlated (R^2 = 0.8508).

Table 1. Hydraulic habitat preferences for Yellow River carp. Adult and juvenile preferences from (Jiang et al., 2010) and spawning preferences based on literature review (see Gippel et al., 2012).

Criterion	Adult	Juvenile	Spawning
Depth (m)	>1.5	1.0 – 2.0	0.3 – 2.0
Velocity (m/s)	0.1 – 0.8	0.1 – 0.6	<0.3
Season	All year	All year	April to June

The hydraulic habitat relationships for Yiluo suggest that a fairly high percentage of the total river area is suitable for Yellow River carp adult and spawning life stages (Figure 5). Also, the availability of suitable habitat area is not particularly discharge dependent. In contrast, at Huayuankou, a low percentage of the total river area is suitable for Yellow River carp, and the availability is highly discharge dependent (Figure 6). At Lijin, a low percentage of the total river area is suitable for Yellow River carp, and the availability of habitat varies erratically with discharge (Figure 7).

The modelled annual habitat availability index scores suggest that habitat was not limiting at Yiluo (Figure 8), while at Huayuankou, habitat availability was variable from year to year (Figure 9). It Lijin, regulation of the river had a noticeable impact on carp habitat availability, especially for juvenile and spawning life stages (Figure 10). These modelled time series of habitat suitability represent the pattern of habitat availability as influenced by discharge alone (i.e. assuming 2010 physical form), whereas actual historical hydraulic habitat availability was also determined by the physical form, which is known to have changed over time (see Gippel et al., 2012).

Figure 5. Ecohydraulic relationships for Yellow River carp habitat at Yiluo.

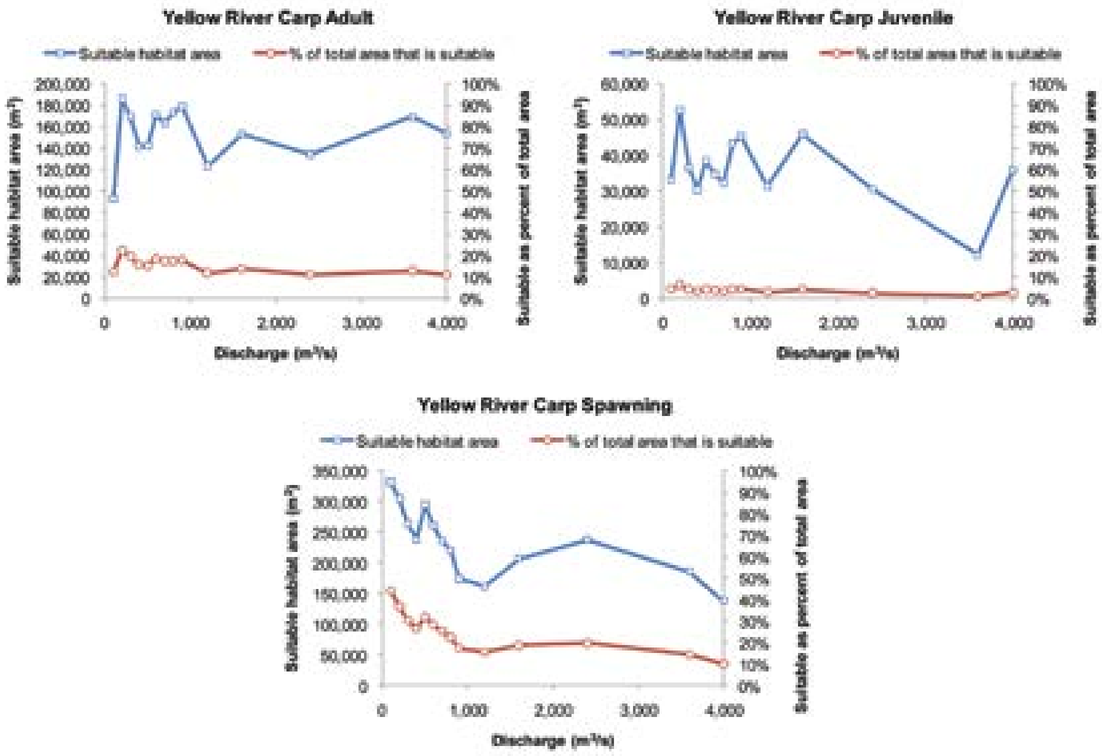


Figure 6. Ecohydraulic relationships for Yellow River carp habitat at Huayuankou.

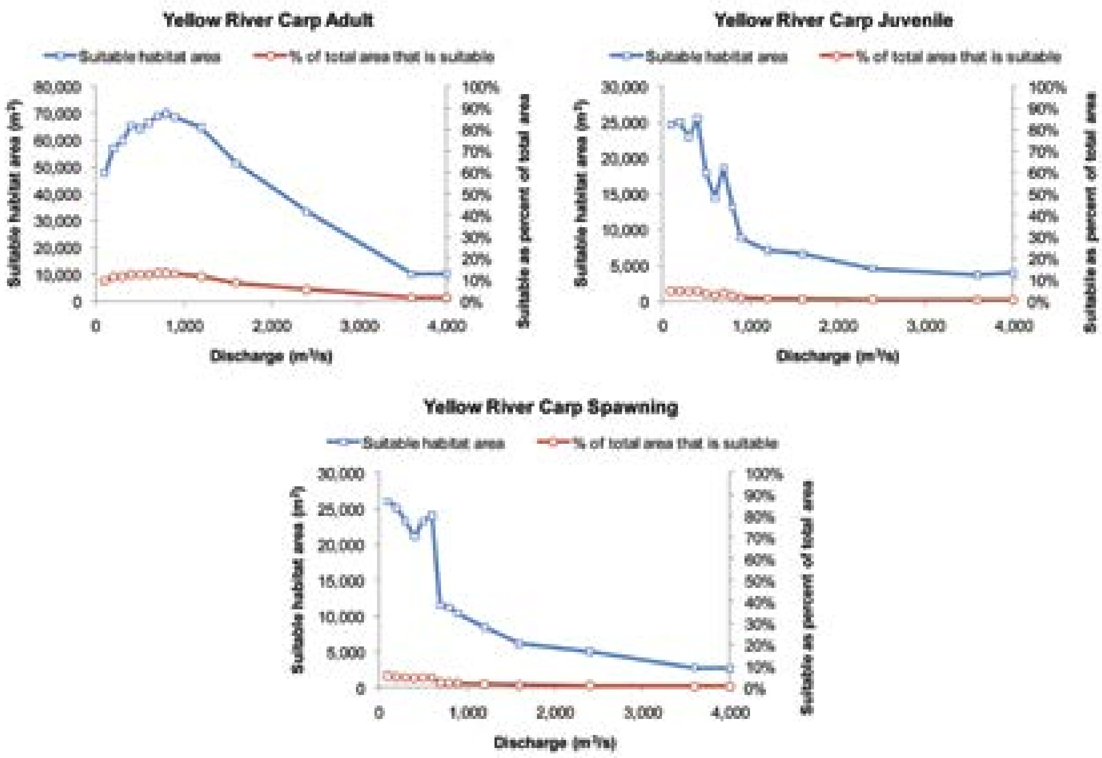
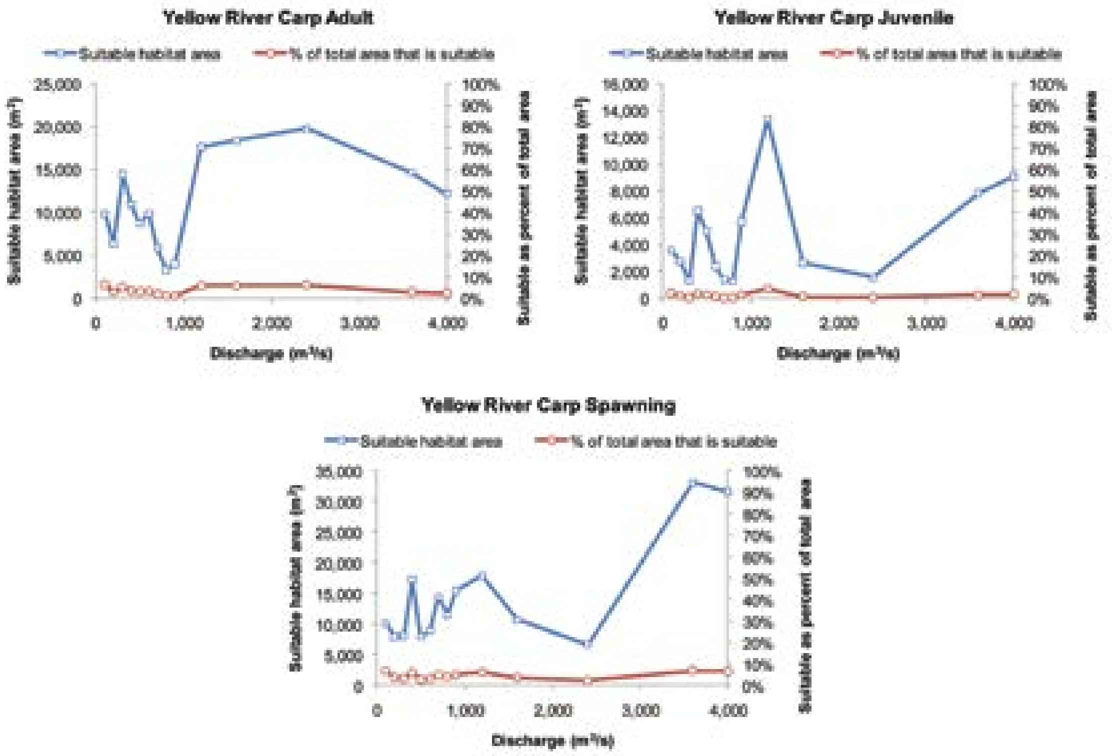


Figure 7. Ecohydraulic relationships for Yellow River carp habitat at Lijin.



Evaluation of Environmental Flow Objectives

Rationalisation of objectives

The environmental flow objectives for the lower Yellow River were specified by Gippel et al. (2012) for six categories:

- Geomorphologic objectives,
- Water quality objectives,
- Waterbird objectives,
- Fish objectives,
- Macroinvertebrate objectives, and
- Vegetation objectives.

The objectives for these categories covered the needs of all of the identified ecological assets.

The geomorphologic objectives and water quality objectives were based on previous work in the lower Yellow River, so hydraulic analysis was not required, and they were specified directly in terms of hydrological needs.

Waterbird objectives were closely tied to vegetation and geomorphologic objectives, and a number of these were aimed at maintaining habitats in the Delta (Reach 4). The Yellow River Delta wetlands are managed through controlled inflows rather than through natural inundation. The issue of how best to manage water distribution in the Delta for the benefit of vegetation and waterbird communities was outside the scope of this project. So, the main objectives to consider for waterbirds were in relation to flows to supply adequate sediment for Delta renewal, and an annual event exceeding 3,000 m^3/s to allow gravity feed of water to the wetlands. The other waterbird objectives related to maintenance of habitats in riverine wetlands in Reach 1. These habitats essentially rely on maintenance of healthy vegetation communities, and slow recession of high flows.

Figure 8. Modelled historical habitat availability index for Yellow River carp at Yiluo.

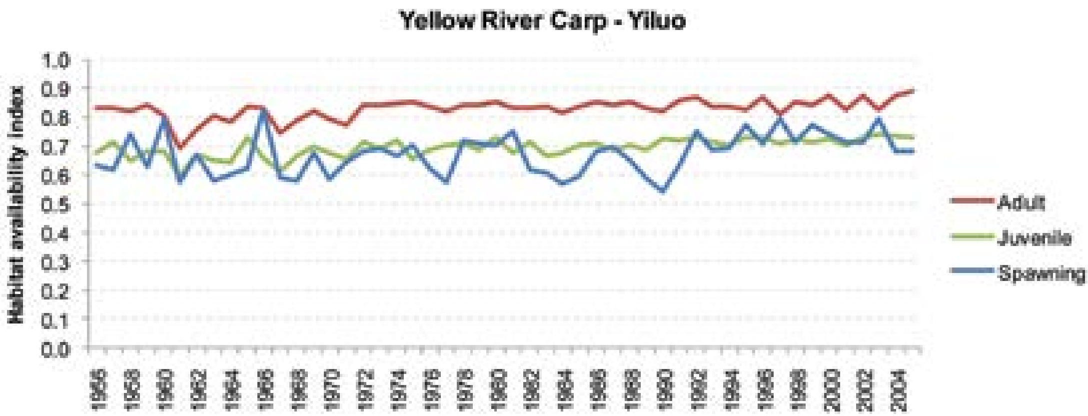


Figure 9. Modelled historical habitat availability index for Yellow River carp at Huayuankou.

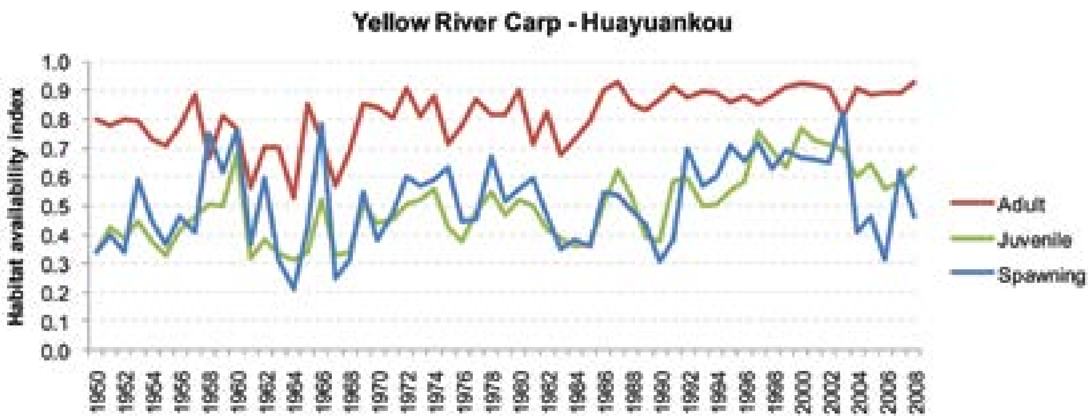


Figure 10. Modelled historical habitat availability index for Yellow River carp at Lijin.

Fish objectives were the most numerous of the environmental flow objective categories. This is explained by the relatively high value people assign to fish, and by the availability of information concerning hydraulic habitat requirements. Some of the fish objectives were in common with some of the geomorphic objectives, and vegetation (wetland inundation) objectives. The objectives of mixing of water in pools and prevention of cease to flow would be met by the minimum baseflow objectives.

Macroinvertebrate objectives were based on providing a reasonable width of wet channel and maintaining favourable salinity at the estuary and river mouth for rearing of Chinese shrimp. Other Delta (Reach 4) objectives were met by geomorphologic objectives. The objectives of mixing of water in pools and prevention of cease to flow would be met by the minimum baseflow objectives.

As indicated above, the vegetation objectives for the Delta were met by flows to supply adequate sediment for Delta renewal, and an annual event exceeding 3,000 m^3/s to allow gravity feed of water to the wetlands. The other vegetation objectives applied to the riverine wetlands in Reach 1.

Based on the above considerations, the objectives specified for the six categories were rationalised into 13 key objectives, with each meeting one or more objectives (Table 2). Some of these objectives were already fully specified as flow components on the basis of existing information, while others required hydraulic and hydrologic analysis to complete their specifications as flow components (Table 2).

Hydraulic modelling of flow magnitude for key objectives

The hydraulic models were used to convert the ecological objectives, as expressed as ecohydraulic objectives, into flow magnitudes (Table 3). In most cases this was simply a matter of interrogating the modelled hydraulic relationships (either 1-D or 2-D model). However, Key Objective F (minimum flows for each month) required some additional manipulation of the 1-D model output. The procedure was to use the 1-D model to determine, for each of the 365 cross-sections, the water surface elevation, and then wetted perimeter, of the pre-Sanmenxia median baseflow for each month. The pre-Sanmenxia median baseflow for each month for each reach was previously calculated by Gippel et al. (2012). These values of wetted perimeter were then factored by 0.8 (the allowable reduction in wetted perimeter that presents a relatively low risk to stream health, as agreed by the Scientific Panel). The 1-D model was then used to calculate, for each cross-section, the value of discharge that would provide this reduced wetted perimeter. Within reaches there was considerable variation in the discharge that would provide the specified reduced wetted perimeter. A single value of discharge for each reach was derived by weighting the calculated discharge for each cross-section according to the length of channel that cross-section represented. In effect, this procedure provided an area weighted average discharge for each reach (Table 4).

The procedure for calculating the magnitude of the Low flow and High flow components described above was preferable to the simpler and more direct approach of factoring of discharge, because wetted perimeter is more directly related to habitat area than is discharge. In this way, the flow reduction is sensitive to the physical form of the channel. For example, a rectangular-shaped channel can tolerate a large reduction in discharge with little reduction in wetted area, while the wet area of a trapezoidal channel with large width/depth ratio would be very sensitive to discharge reduction. In the case of the lower Yellow River, Reach 1 is wider and shallower compared to Reaches 2, 3 and 4. Thus, this method resulted in lower relative reductions in baseflow for Reach 1 compared to Reaches 2, 3 and 4 (Figure 11).

The approach to environmental flow assessment taken here was to provide an environmental flow option that would protect the health of ecological assets at low risk, and at least one alternative option that would carry a higher risk to ecological health. In some situations, river managers and the wider community of river users might be willing to trade a higher risk to river health against the socio-economic benefits that can be achieved through having more water available for human uses. The baseflow regime for the alternative, medium-risk, flow option was derived in the same way as for the low-risk option, but wetted perimeter was factored by 0.6 (Table 5).

Table 2. Key flow objectives and flow requirements to maintain the health of the lower Yellow River. D = depth, V = velocity; Q = discharge.

Key obj.	Obj. met	Objectives description	Flow component	Hydrologic criteria	Mean annual frequency/ duration	Inter-annual frequency	Timing	Reach
A	F1; M1	Prevent habitat loss through drying of shallow areas	Cease to flow	Q ≥ YRCC warning standards of low flow emergency to prevent cease to flow	Continuous	100% of the time	All year	All reaches
B	B1; B2; B3	Expose Carex and mudflats; shallow water over submerged aquatics	Low flow	Exposure of “soft beach”	Continuous	≥ 75% of the time	Nov - Jun	Reach 1
C	F2	Maintain shallow habitats with moderate-high velocity for shallow water dwelling species and spawners during low flow periods	Low flow	Provide areas with with D = 0.5 – 1.5 m and V ≤ 2.0 m/s	Continuous	≥ 75% of the time	All year	Reaches 1 - 3
D	WQ1, WQ2, WQ3, WQ4	Dilute contaminants to Grade III standard	Low flow and high flow	≥ 320 m^3/s (Reach 1); ≥ 234 m^3/s (Reach 2); ≥ 146 m^3/s (Reach 3); ≥ 60 m^3/s (Reach 4)	≥ 90% of time	≥ 75% of the time	All year	All reaches
E	V3; V4	Maintain *Tamarix/Salix* shrubland and woodland	Low flow and high flow	Maintain shallow groundwater at 0.5 (Jul-Sep) and 1.5 – 3.0 m (all year) from surface of “second beach”	Variable	-	All year	Reach 1
F	M2; M5; F3; F4; F11; F16	Maintain reasonable area of habitat for most of the time for longitudinal connectivity, survival of large-bodied fish, maintenance of primary productivity in the estuary; and maintenance of DO levels in deep pools	Low flow and high flow	≥ 80% of wetted area at pre-Sanmenxia median baseflow for each month	Continuous	≥ 75% of the time	Each month	All reaches

Key obj.	Obj. met	Objectives description	Flow component	Hydrologic criteria	Mean annual frequency/ duration	Inter-annual frequency	Timing	Reach
G	F6; F7; F9	Provide suitable habitats for spawning, allow access of large bodied fish to backwater and wetland habitats; maintain downstream transport of semi-buoyant eggs within the water column; and sufficient depth in pools for large-bodied fish	High flow	Provide areas with D = 0.5 – 1.5 m and V = 0.5 – 2.0 m/s	Continuous	≥ 75% of the time	Apr-Sep	All reaches
H	V1; B5; M3; M4; F14	Maintain submerged aquatic vegetation	High flow	Inundation of “soft beach” to D ≤ 1 m	Continuous	≥ 75% of the time	Jul – Oct	Reach 1
I	V2	Maintain meadow vegetation	High flow	Inundation of “second beach” to D ≤ 0.3 m	50 – 100% of time	≥ 75% of the time	Jun – Nov	Reach 1
J	M6; F8	Maintain favourable salinity at estuary and mouth for rearing of Chinese shrimp; and maintain salinity gradient for anadromous fish spawning migration	High flow	191 ≤ Q ≤ 1227 m^3/s	≥ 50% of the time	≥ 75% of the time	April – Aug	Reach 4
K	V3; V4; F10	Maintain *Tamarix/Salix* shrubland and woodland; and replenish/maintain water in river associated wetlands and backwaters	Low flow pulse	Inundation of “second beach”	≥ 1 per year / ≤ 30 days	≥8 in 10 years	Nov - May	Reach 1
L	F5; F10	Stimulate spawning, migration (anadromy and potadromy) and maintain habitat continuity between near-shore/ estuarine and freshwater habitats to allow free upstream passage; and replenish/maintain water in river associated wetlands and backwaters	High flow pulse	Achieve D ≥ 1.0 m at shallow sections	≥ 1 per year / 10 – 20 days duration[1]	≥ 8 in 10 years	Apr-Jun	All reaches
M	G1, G2, G3, G4, WQ6; B6; B7; B8; M7; M8; F12; F13;	Scour and deposition processes to maintain dynamic and diverse habitats in the channel and connected floodplains; maintain channel capacity at 4,000 m^3/s; seaward progradation of the delta; allow flow into delta wetland channels for habitat provision and physical maintenance; provide low velocity littoral habitats for small bodied species; and maintain shallow pool crossings with moderate-high velocities	Bankfull	3,000 - 4,000 m^3/s Sediment load >3.45 × 10^8 tonnes at Lijin; event mean sediment concentration ≥ 35 kg/m^3 and peak concentration ≤ 110 kg/m^3	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥8 in 10 years	Jun – Sep	All reaches

Table 3. Calculated, or previously known, flow magnitudes associated with each key flow requirements to maintain the health of the lower Yellow River. XLD = Xiaolangdi; HYK = Huayuankou; GC = Gaocun; SK = Sunkou; LK = Luokou; LJ = Lijin.

Obj.	Component	Model used	Reach	Desirable discharge range (m^3/s) (gauge for compliance)
A	Cease to flow	Previously known	Reach 1	≥ 150 (HYK)
			Reach 2	≥ 120 (GC) and ≥ 80 (SK)
			Reach 3	≥ 100 (LK)
			Reach 4	≥ 30 (LJ)
B	Low flow	1-D	Reach 1	< 500 (XLD and HYK)
C	Low flow	2-D	Reach 1	Any discharge (peak at low Q) (XLD)
			Reach 1	Any discharge (high at 700 – 2,000; peak at 1,000) (HYK)
			Reach 2	Model not available (assume same as Reach 3) (SK)
			Reach 3	Low at 1,200 – 2,400; high at 100 – 900; peak at 500) (LK))
D	Low flow and high flow	Previously known	Reach 1	≥ 300 (XLD) and ≥ 320 (HKY)
			Reach 2	≥ 234 (GC) and ≥ 146 (SK)
			Reach 3	≥ 146 (LK)
			Reach 4	≥ 60 (LJ)
E	Low flow	1-D	Reach 1	300 – 1,000 (XLD and HYK)
	High flow	1-D	Reach 1	≥ 1600 (XLD and HYK)
F	Low flow and high flow	1-D	All	See Table 4 for monthly minimum flows
G	High flow	2-D	Reach 1	Any discharge (high at 100 – 900; peak at 300) (XLD)
			Reach 1	Any discharge (high at 500 – 2,400; peak at 900) (HYK)
			Reach 2	Model not available (assume same as Reach 3) (SK)
			Reach 3	Low at 1200 – 2400; high at 100 – 900; peak at 600) (LK)
			Reach 4	Model not available (assume same as Reach 3) (LJ)
H	High flow	1-D	Reach 1	300 – 900 (XLD and HYK)
I	High flow	1-D	Reach 1	2,000 – 3,000 (XLD and HYK)
J	High flow	Previously known	Reach 4	191 – 1,227 (LJ)
K	Low flow pulse	1-D	Reach 1	≥ 2,000 (XLD and HYK)
L	High flow pulse	1-D	Reach 1	≥ 400 (XLD and HYK)
			Reach 2	≥ 500 (SK)
			Reach 3	≥ 400 (LK)
			Reach 4	≥ 50 (LJ)
M	Bankfull	Previously known	All	3,000 – 4,000 (XLD, HYK, SK, LK, LJ)

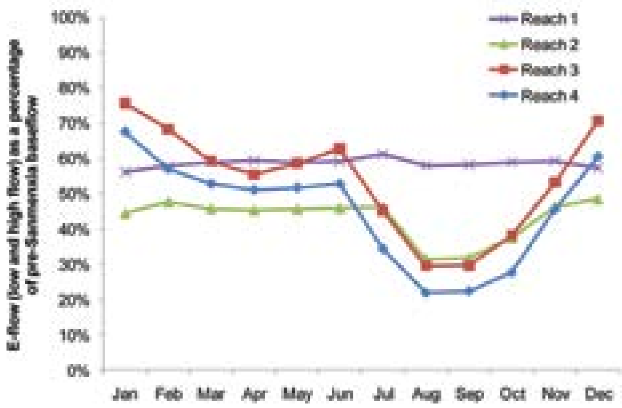
Table 4. Monthly minimum discharges that provide 80 percent of pre-regulation wetted area at baseflow, to achieve baseflow-dependent ecological flow objectives at low-risk.

Month	Minimim monthly discharge to provide low-risk area of wetted channel (m^3/s)			
	Reach 1	Reach 2	Reach 3	Reach 4
Jan	280	154	219	189
Feb	321	229	362	314
Mar	377	273	410	332
Apr	463	342	427	379
May	430	285	417	342
Jun	434	266	394	332
Jul	783	362	509	436
Aug	1,137	584	603	447
Sep	1,124	580	601	446
Oct	866	532	543	441
Nov	543	362	445	412
Dec	307	216	343	303

Table 5. Monthly minimum discharges that provide 60 percent of pre-regulation wetted area at baseflow, to achieve baseflow-dependent ecological flow objectives at medium-risk.

Month	Minimim monthly discharge to provide medium-risk area of wetted channel (m^3/s)			
	Reach 1	Reach 2	Reach 3	Reach 4
Jan	174	86	143	116
Feb	191	115	234	217
Mar	229	130	260	224
Apr	284	159	277	239
May	263	133	264	227
Jun	265	128	248	224
Jul	466	165	324	278
Aug	754	310	355	284
Sep	744	309	355	283
Oct	534	276	337	281
Nov	335	165	283	263
Dec	185	108	225	212

Figure 11. The low-risk recommended minimum monthly flows (low flow and high flow components) as a percentage of the pre-regulation median baseflows for each month.



Recommended Environmental Flow Options

The hydraulic analysis suggested that some flow objectives were met automatically by other objectives requiring higher discharge magnitudes. This allowed merging of some flow components. While it is important that the recommended flow regime meet as many objectives as possible, fewer and simpler components allow for more straightforward implementation.

Provision of the recommended minimum baseflow components (High flows and Low flows) will prevent the occurrence of cease to flow. The existing warning flow thresholds used by YRCC were considered adequate to manage cease to flow emergencies.

The recommended low-risk flow regime for Reach 1 satisfied all of the identified objectives, except for V4 and V2. V4 requires a High flow component of ≥ 1600 for 3 months to maintain *Tamarix/Salix* woodland (raise water table to within 0.5 m of “second beach”) in the riverine wetlands, and V2 requires a High flow component of 2,000 – 3,000 m^3/s for 6 months to maintain meadow vegetation (inundate the “second beach”) in the riverine wetlands. The flow components are partly met because the annual WSDR event (Bankfull component) occurs during the High flow season, but the duration is usually less than 1 month. The recommended low-risk flow regime for Reaches 2, 3 and 4 satisfy all of the identified objectives.

The recommended medium-risk flow regimes were formulated by reducing baseflows, and in the case of Reach 1, by eliminating the Low flow pulse. Elimination of the Low flow pulse is to the detriment of the health of the riverine wetlands because the pulse helps to maintain *Tamarix/Salix* shrubland and *Tamarix/Salix* woodland (Gippel et al., 2012). This flow component also achieves sufficient depth to replenish/maintain water in river-associated wetlands and backwaters for the benefit of small-bodied fish species such as Sharpbelly and Cobitids (Gippel et al., 2012).

The environmental flow options presented here address only hydrological aspects of the needs of ecological assets. Water quality, temperature and physical habitat are also important aspects of managing river health, and they need to be addressed jointly with implementation of environmental flows. These aspects were reviewed in detail in the site, assets, issues and objectives paper for the lower Yellow River (Gippel et al., 2012).

Table 6. Low-risk environmental flow regime for Reach 1 of the lower Yellow River. Compliance point is Huayuankou.

Objectives met	Flow component	Hydrologic criteria	Mean annual frequency/ duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
B1; B2; B3, F2; WQ1, WQ2, WQ3, WQ4; V3; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 307 Jan ≥ 280 Feb ≥ 321 Mar ≥ 377 Apr ≥ 463 May ≥ 430	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9; V1; B5; M3; M4; F14	High flow	Jun ≥ 434 Jul ≥ 783 Aug ≥ 1,137 Sep ≥ 1,124 Oct ≥ 866 Nov ≥ 543	Continuous	≥ 75% of the time	Jun - Nov
V3; V4; F10	Low flow pulse	≥ 2000	≥ 1 per year / 1 – 30 days; rates of rise and fall within natural range	≥4 in 5 years	Nov - May
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3000 – 4000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep

Table 7. Medium-risk environmental flow regime for Reach 1 of the lower Yellow River. Main risk is to Reach 1 riverine wetlands. Compliance point is Huayuankou.

Objectives partly met	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
B1; B2; B3, F2; WQ1, WQ2, WQ3, WQ4; V3; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 185 Jan ≥ 174 Feb ≥ 191 Mar ≥ 229 Apr ≥ 284 May ≥ 263	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9; V1; B5; M3; M4; F14	High flow	Jun ≥ 265 Jul ≥ 466 Aug ≥ 754 Sep ≥ 744 Oct ≥ 534 Nov ≥ 335	Continuous	≥ 75% of the time	Jun - Nov
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3,000 – 4,000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep
V3; V4; F10	Not provided				

Table 8. Low-risk environmental flow regime for Reach 2 of the lower Yellow River. Compliance point is Sunkou.

Objectives met	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
F2; WQ1, WQ2, WQ3, WQ4; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 216 Jan ≥ 154 Feb ≥ 229 Mar ≥ 273 Apr ≥ 342 May ≥ 285	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9	High flow	Jun ≥ 266 Jul ≥ 362 Aug ≥ 584 Sep ≥ 580 Oct ≥ 532 Nov ≥ 362	Continuous	≥ 75% of the time	Jun - Nov
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3000 – 4000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep

Table 9. Medium-risk environmental flow regime for Reach 2 of the lower Yellow River. Compliance point is Sunkou.

Objectives partly met	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
F2; WQ1, WQ2, WQ3, WQ4; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 108 Jan ≥ 86 Feb ≥ 115 Mar ≥ 130 Apr ≥ 159 May ≥ 133	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9	High flow	Jun ≥ 128 Jul ≥ 165 Aug ≥ 310 Sep ≥ 309 Oct ≥ 276 Nov ≥ 165	Continuous	≥ 75% of the time	Jun - Nov
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3000 – 4000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep

Table 10. Low-risk environmental flow regime for Reach 3 of the lower Yellow River. Compliance point is Luokou.

Objectives met	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
F2; WQ1, WQ2, WQ3, WQ4; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 343 Jan ≥ 219 Feb ≥ 362 Mar ≥ 410 Apr ≥ 427 May ≥ 417	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9	High flow	Jun ≥ 394 Jul ≥ 509 Aug ≥ 603 Sep ≥ 601 Oct ≥ 543 Nov ≥ 445	Continuous	≥ 75% of the time	Jun - Nov
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3000 – 4000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep

Table 11. Medium-risk environmental flow regime for Reach 3 of the lower Yellow River. Compliance point is Luokou.

Objectives partly met	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
F2; WQ1, WQ2, WQ3, WQ4; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 225 Jan ≥ 143 Feb ≥ 234 Mar ≥ 260 Apr ≥ 277 May ≥ 264	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9	High flow	Jun ≥ 248 Jul ≥ 324 Aug ≥ 355 Sep ≥ 355 Oct ≥ 337 Nov ≥ 283	Continuous	≥ 75% of the time	Jun - Nov
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3000 – 4000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep

Table 12. Low-risk environmental flow regime for Reach 4 of the lower Yellow River. Compliance point is Lijin.

Objectives met	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
WQ1, WQ2, WQ3, WQ4; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 303 Jan ≥ 189 Feb ≥ 314 Mar ≥ 332 Apr ≥ 379 May ≥ 342	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9, M6, F8	High flow	Jun ≥ 332 Jul ≥ 436 Aug ≥ 447 Sep ≥ 446 Oct ≥ 441 Nov ≥ 412	Continuous	≥ 75% of the time	Jun - Nov
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3000 – 4000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep

Table 13. Medium-risk environmental flow regime for Reach 4 of the lower Yellow River. Compliance point is Lijin.

Objectives partly met	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
WQ1, WQ2, WQ3, WQ4; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 212 Jan ≥ 116 Feb ≥ 217 Mar ≥ 224 Apr ≥ 239 May ≥ 227	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9, M6, F8	High flow	Jun ≥ 224 Jul ≥ 278 Aug ≥ 284 Sep ≥ 283 Oct ≥ 281 Nov ≥ 263	Continuous	≥ 75% of the time	Jun - Nov
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3,000 – 4,000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep

Environmental Flow Compliance

Method of compliance

As a component of the ACEDP project, Gippel et al. (2011) developed an Index of Flow Health (IFH) as a means of measuring the degree of compliance of environmental flow components with an agreed standard. Compliance means the frequency that environmental flow components appeared in the historical flow time series, relative to the frequency recommended for implementation (which was designed to achieve the agreed level of river health). As the environmental flow event objectives are specified in multi-dimensional terms of magnitude, duration, annual frequency and inter-annual frequency, IFH uses a sophisticated form of spells analysis to determine the compliance of each of the flow components. This method of compliance analysis was first documented by Gippel et al. (2009). The details of the IFH method are not provided in this report, but can be found in Gippel et al. (2011). The compliance of historical flows with the recommended environmental flows was evaluated using a daily flow series, with the results presented as an annual score. The annual score for baseflows for each month reflected the percent of time in each month that compliance was met. For events (flow pulses and Bankfull), the annual score was a reflection of the frequency of occurrence of the recommended event in that year plus the previous four years. This is because the recommended inter-annual frequency of these flow components was expressed as the number of events that occurred in every 5 rolling years.

The baseflow (Low flow and High flow components) recommendations were specific to each month. The compliance of the Low flow (low flow season) and High flow (high flow season) components was evaluated for each month of every year in the historical time series. The purpose of this was to assess if any particular month or months of the year had low compliance. Also, a combined Low flow index value was calculated for each year as the average of the index values for the low flow season months, and a combined High flow index value was calculated as the average of the index values for the high flow season months. These combined index values were used in the evaluation of the entire environmental flows regime.

The rates of rise and rate of fall flow components are more properly characteristics of event components (Bankfull and Pulses), but they were evaluated as separate components because they are an independently manageable aspect of the river flow. However, when calculating an overall annual IFH score, the scores for rates of rise and fall are used as modifiers of the event components (pulses and bankfull components). So, if the rates of rise or fall were close to reference, they scored 1 and did not reduce the score of the event components. However, if the rates of rise and fall were impaired relative to reference, then their lower scores caused a reduction in the scores for the corresponding event components. Cease to flow, High flows, Low flows, Pulses and Bankfull flows are all important for maintenance of ecological health of the lower Yellow River system, as each of these components satisfies multiple ecological, water quality and geomorphological objectives (see Gippel et al., 2011). As there was no ecological basis for considering any of these components more or less important than others, they were given equal weightings. In another river system, alternative weightings might be used. Thus, an integrated IFH index score () was derived by weighting the individual IFH indicator scores according to the following relationship:

$$IFH_1 = \frac{a_1 CTF + a_2 LF + a_3 HF + a_4 \left(\frac{LFR + LFF}{2}\right) LFP + a_5 \left(\frac{HFR + HFF}{2}\right) HFP + a_6 \left(\frac{HFR + HFF}{2}\right) BF}{b}$$

where,

a_1, a_2, a_3, a_4, a_5, a_6 = weighting coefficients specific to each IFH flow component (Table 14)
$b = a_1 + a_2 + a_3 + a_4 + a_5 + a_6$ (Table 14)
CTF = Cease to flow score
LTF = Low flow rate of rise score
LFF = Low flow rate of fall score
LF = Low flow score
LFP = Low flow pulse score
HFR = High flow rate of rise score
HFF = High flow rate of fall score
HFP = High flow pulse score
HF = High flow score
BF = Bankfull flow score

Table 14. Weighting coefficients used to calculate integrated IFH score for the lower Yellow River.

	Cease to flow	Low flow	Low flow pulse	High flow	High flow pulse	Bankfull	
	CTF	LF	LFP	HF	HFP	BF	b
Reach (e-flow option)	a_1	a_2	a_3	a_4	a_5	a_6	
1 (low-risk)	1.0	1.0	1.0	1.0	0.0	1.0	5
1 (med-risk)	1.0	1.0	0.0	1.0	0.0	1.0	4
2 (low-and med-risk)	1.0	1.0	0.0	1.0	0.0	1.0	4
3 (low-and med-risk)	1.0	1.0	0.0	1.0	0.0	1.0	4
4 (low-and med-risk)	1.0	1.0	0.0	1.0	0.0	1.0	4

Evaluation of annual compliance analysis was performed for water years, which for the lower Yellow River begins in December. The compliance of High flow and Low flow components was also evaluated by month; in this case the results were presented for calendar years.

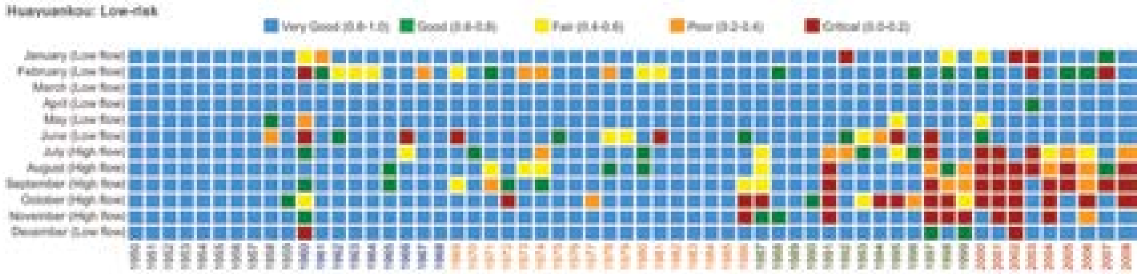
The annual compliance time series for the lower Yellow River were calculated for four gauges: Huayuankou, Sunkou, Luokou and Lijin, which represented Reaches 1, 2, 3 and 4, respectively. The compliance was measured for both the low-risk and medium-risk environmental flow options. In the compliance plots below, the main dam regulation phases are indicated using coloured text for the date scale: grey text = pre-Sanmenxia (SMX); blue text = post-SMX and pre-Liujiaxia (LJX); orange text = post-LJX and pre-Longyangxia (LYX); green text = pre-Xiaolangdi (XLD) and post-LYX and red text = post- XLD. Compliance was measured as an index score over the range 0 – 1, and the score was then placed within a 5-class scale, ranging from very good (perfect or close to perfect compliance) to critical (flows diverge greatly from the recommended environmental flows).

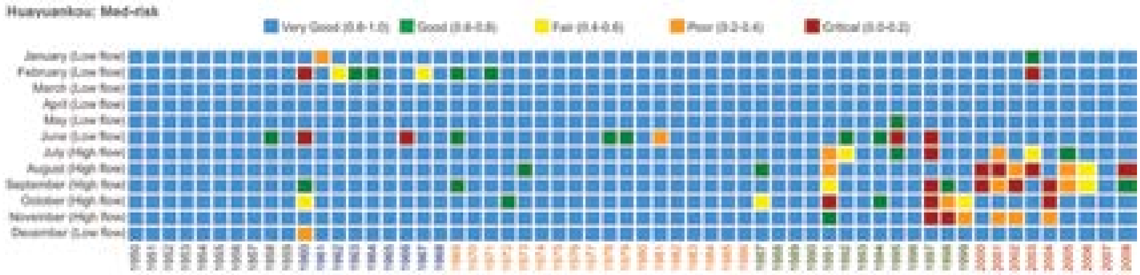
Monthly compliance of High flow and Low flow components

The compliance check of Low and High flow components by month indicated that non-compliance did not occur until 1958 (Figure 12; Figure 13; Figure 14 and Figure 15). Under the period of the Great Leap Forward (1958 to 1961) the irrigated area in the Yellow River basin increased 58 times from 37,500 ha in 1957 to 2,170,000 ha at the end of 1959 (Bin et al., 2003). In 1959, 1960 and 1961 the volume of water diverted from the river rose dramatically (Gippel et al., 2012). The wall of Sanmenxia dam was closed in October 1960, and filling of the reservoir might partly explain the poor compliance result in the months that followed. However, it was the sudden diversion of massive volumes of water for new irrigation areas that was mainly responsible for the poor compliance in 1960 through to early 1961. The remarkable expansion of water utilisation in the three-year period 1959-1961 produced a dramatic rise in the water table, with waterlogging and salinity rendering large areas unproductive (Bin et al., 2003). In 1962 the Henan Provincial Government ordered the closure of most of the water diversion systems along the Yellow River, and the irrigation districts were instructed to undertake salinity control measures (Bin et al., 2003). After 1965 the irrigation districts resumed operation and the agricultural production grew steadily (Bin et al., 2003). The expansion of irrigation was facilitated by ongoing regulation of the river through dam construction. In the 1970s conjunctive use of surface and groundwater was adopted in the lower Yellow River (Luo et al., 2006). After increasing steadily since 1965, water utilisation in the lower Yellow River began to decline after 1989. This coincided with a step-change decline in basin runoff in 1990 (Gippel et al., 2012). While the absolute volume of water utilised began a declining trend in 1989, the percentage of the flow taken from the river continued to increase, reaching a peak in 1997, when, at Lijin, 94% of the natural flow was utilised, and at Huayuankou it was 58% (Gippel et al., 2012). The monthly High flow and Low flow compliance plots (Figure 12; Figure 13; Figure 14 and Figure 15) reflect these historical patterns in water resource availability and utilisation. Anecdotal information (see Gippel et al., 2012) suggests that the historical trend of declining ecological health of the lower Yellow River mirrored the pattern of hydrological impairment evident in the time series of IFH scores (Figure 12; Figure 13; Figure 14 and Figure 15).

Reach 1

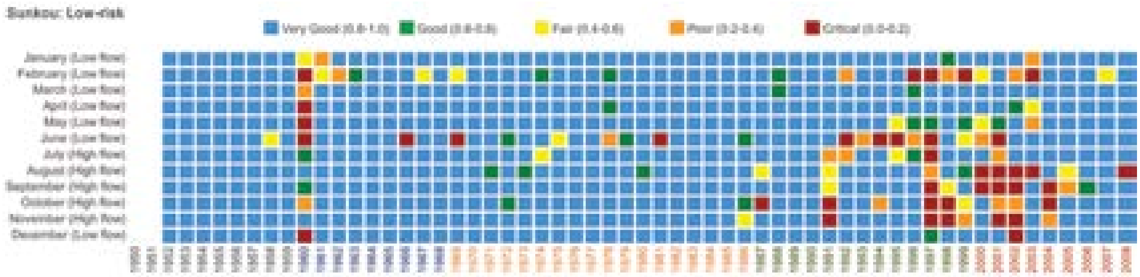
Figure 12. Time-series of monthly High flow and Low flow compliance at Huayuankou (Reach 1) for low- (top) and medium-risk (bottom) environmental flow regime.

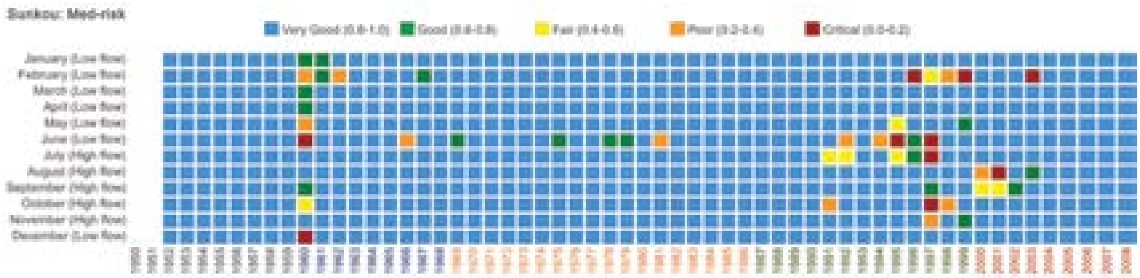




Reach 2

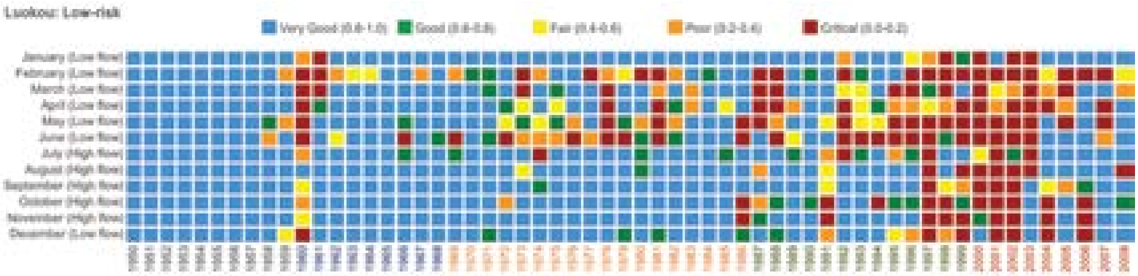
Figure 13. Time-series of monthly High flow and Low flow compliance at Sunkou (Reach 2) for low- (top) and medium-risk (bottom) environmental flow regime.

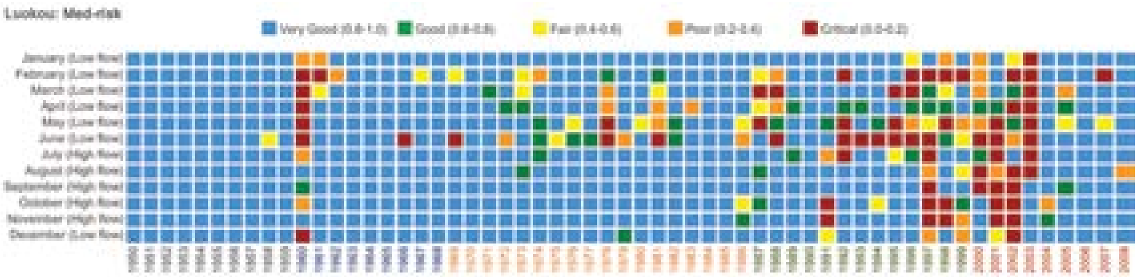




Reach 3

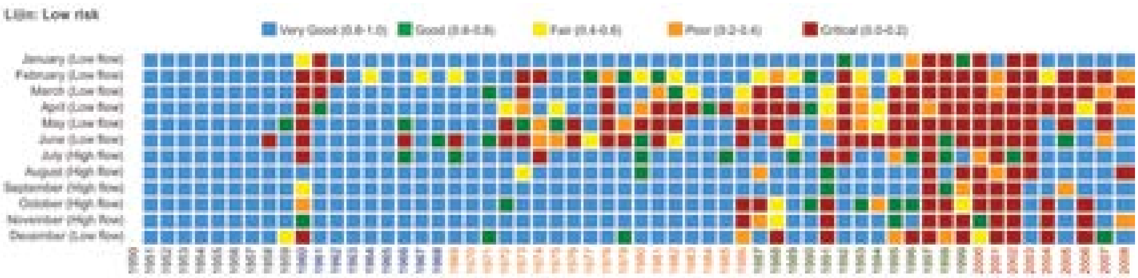
Figure 14. Time-series of monthly High flow and Low flow compliance at Luokou (Reach 3) for low- (top) and medium-risk (bottom) environmental flow regime.

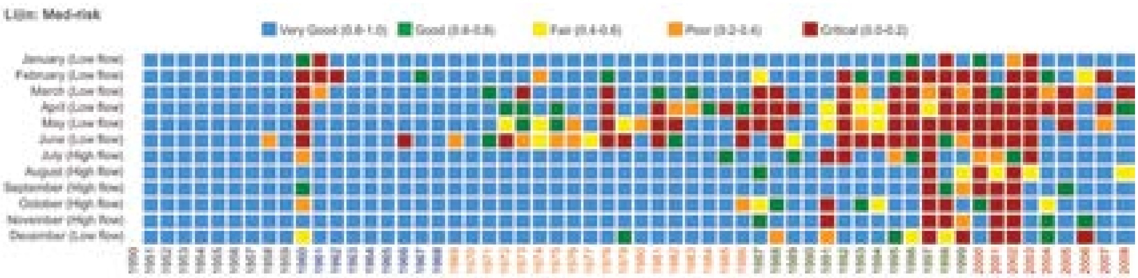




Reach 4

Figure 15. Time-series of monthly High flow and Low flow compliance at Lijin (Reach 4) for low- (top) and medium-risk (bottom) environmental flow regime.





Annual compliance of all environmental flow components

The monthly scores for High and Low flow components were aggregated into two scores for the year, one for the high flow season, and one for the low flow season. The IFD scores of these components were then compiled with the IFH scores for the other environmental flow components, and weighted according to Equation (1). The annual compliance time series for all environmental flow components indicated that historically, the main problems with non-compliance were associated with Bankfull flow, High flow, Low flow and Cease to flow components (Figure 16, Figure 17, Figure 18 and Figure 19).

Overall, compliance with rates of rise and fall was high, although there were some instances of higher than desirable rates of rise and fall at Sunkou

Compliance with the Low flow pulse component at Huayuankou was poor to critical in most years since operation of Xiaolangdi dam began. However, the compliance of this component was also often lower than desirable prior to operation of Xiaolangdi dam. The Low flow pulse component was intended to inundate a riparian vegetation community, so had to reach a certain elevation in the channel. It was specified relative to the channel form in 2010. This component required a relatively high magnitude (and thus low compliance) because the channel had incised significantly since the WSDR began in 2002, so higher magnitude flows are now required in order to reach the same elevation as previously. Prior to incision of the channel, this flow component would have been satisfied by a lower discharge threshold, so in reality, prior to 2002, when the channel form was different (i.e. shallower), this component would have had high compliance.

Compliance with the Bankfull component was poor in all reaches following the commencement of operation of Longyangxia dam. In recent years, implementation of the WSDR event has improved the compliance of Bankfull in Reaches 1, 2 and 3. The Bankfull component was specified with a minimum flow of 3,000 m^3/s for 10 days, with this minimum magnitude being a threshold for diverting water to the Delta wetlands. The duration of the event mainly determines the load of sediment that can be scoured from the channel and transported out of Xiaolangdi dam. Although a WSDR event has been implemented annually since 2002, some of these did not reach the magnitude or duration specified in the Bankfull flow component. In reality, the channel capacity has increased significantly since 2002, so it would have been imprudent to release flows of 3,000 m^3/s in the first few years of operation of the dam.

Cease to flow had poor compliance in Reaches 3 and 4 after commencement of operation of Longyangxia dam in 1969, but compliance was very good after Xiaolangdi dam commenced operation in 2000.

Low flows had poor compliance in Reaches 3 and 4, but compliance with this component was generally good or better in Reaches 1 and 2. Low flow compliance improved in Reaches 3 and 4 to fair to good after 2003. High flow compliance was lower than desirable in all reaches from the 1990s onwards. However, compliance improved significantly in all reaches since 2003.

Overall, there was a worsening of compliance in the downstream direction, but this pattern is apparent only after Longyanxia dam began operation. Construction of dams provided the control over flow that allowed irrigation to flourish in the lower Yellow River area. Thus, the downstream reduction in compliance is the result of progressive diversion of water from the river for human uses, combined with a step-change reduction in basin runoff that occurred in 1990.

Having lower standards for ecological health, the medium-risk environmental flow regime had higher compliance than the low-risk regime.

Reach 1

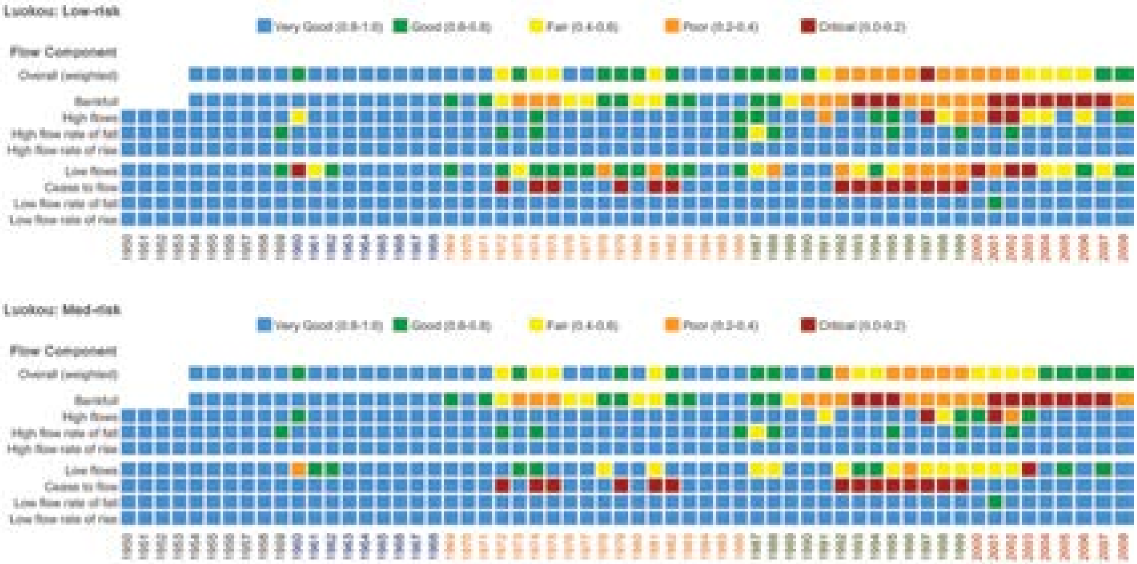
Figure 16. Time-series of annual compliance for all flow components at Huayuankou (Reach 1) for low- (top) and medium-risk (bottom) environmental flow regime.

Reach 2

Figure 17. Time-series of annual compliance for all flow components at Sunkou (Reach 2) for low- (top) and medium-risk (bottom) environmental flow regime.

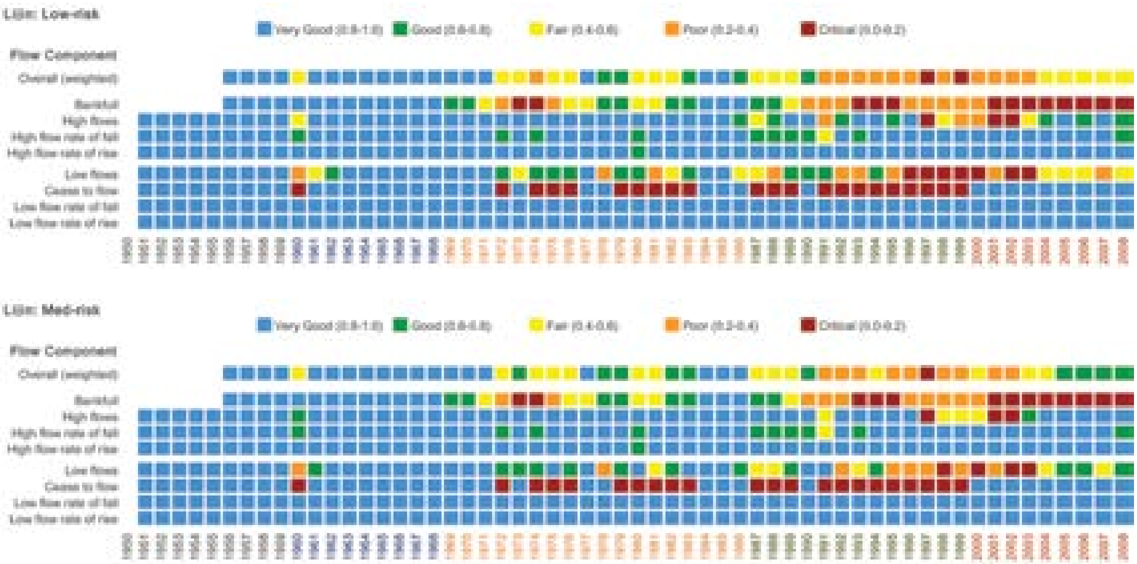
Reach 3

Figure 18. Time-series of annual compliance for all flow components at Luokou (Reach 3) for low- (top) and medium-risk (bottom) environmental flow regime.



Reach 4

Figure 19. Time-series of annual compliance for all flow components at Lijin (Reach 4) for low- (top) and medium-risk (bottom) environmental flow regime.



Discussion and Conclusion

The environmental flow assessment method employed for the lower Yellow River made use of the previous environmental flows work that had been done on the river. The main advancement made here was to consider multiple objectives for a wide range of ecological assets. The process documented in detail the scientific basis for environmental flow assessment on the lower Yellow River, and future re-assessments can readily build on this knowledge base.

The scope for implementing environmental flows on the lower Yellow River is constrained by the need to confine the flows to the main channel, in order to avoid the high social cost of flooding. Sharing the limited water available with irrigation means that environmental flows will be less than ideal in some respects. From the 1970s onwards, the hydrological regime of the lower Yellow River became progressively less conducive to good ecological health. Following construction of Xiaolangdi dam in 1999, conditions improved significantly. This was by design, as environmental flows have been formerly included in management decisions since that time. The implemented environmental flows have been adjusted through time; for example, baseflows were increased significantly from 2004 onwards (Gippel et al., 2012). While monthly baseflows (Low flow and High flow components) improved significantly since Xiaolangdi dam has been operational, some aspects of the flow regime remain less than ideal. Poor compliance is mainly associated with lower than desirable magnitude and duration of the peak flow of the high flow season, and the shorter than desirable summer high flow recession. The high flow season event is now controlled to remain within the channel, so important riverine wetlands in Reach 1 between Xiaolangdi and Gaocun are no longer inundated (apart from a narrow strip of beach close to the river's edge).

Overall, hydrology is currently less limiting to river health than it was prior to operation of Xiaolangdi dam. However, other aspects of the river remain limiting. Riparian wetlands are now extremely limited in extent, and are declining in area and health. This trend will continue as the river becomes deeper due to scour caused by the annual water and sediment regulation event, and as training works to control the channel alignment extend further upstream into the reach from Mengin to Gaocun. This is the main area where management objectives for utilitarian use of the river conflict with those for achievement of river health.

The current environmental flow practice in the lower Yellow River produced reasonably good compliance with the environmental flow regime recommended here. Compliance with the Bankfull event is not always high, mainly because the annual water and sediment regulation event sometimes does not reach the desirable magnitude and duration for delivering flow and sediment to the Delta. Compliance with the High flow component is mainly compromised by the lack of a long duration recession following the annual water and sediment regulation event.

While the hydrological conditions have improved significantly since Xiaolangdi dam began operation, river health could benefit greatly from improved water quality and better access to freshwater riverine wetland and backwater environments. In the lower Yellow River, riverine wetlands can now be found only in limited areas of the reach from Xiaolangdi to Gaocun, and they are shrinking in area due to appropriation of floodplain land for agriculture and aquaculture. If maintained in good condition, these areas provide important waterbird habitat that complements that found in the Yellow River Delta. The health of the Delta relies on annual inflows of water from the river, but also on annual renewal of the mudflats though delivery of an adequate load of sediment from the river. At present, growth of the Delta is barely sufficient to compensate for the area lost through marine erosion.

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