Assessment of river health in the Lower Yellow River

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This report is the result of work undertaken as part of the River Health and Environmental Flow in China Project, that was funded under the Australia-China Environment Development Partnership, an Australian Government AusAID initiative.
Executive Summary

The lower Yellow River study is one of three pilot sub-projects undertaken for the River Health and Environmental Flow in China Project. The lower Yellow River sub-project includes both a river health assessment and an environmental flows assessment. This report covers the river health assessment component. The objective of the study was to establish a method for selecting suitable indicators of river health, and to make an initial assessment of river health for the lower Yellow River.

Rivers provide a range of goods and services that human communities depend on. River health assessments endeavour to assess the ecological condition of a river, and its capacity to continue to provide these valuable goods and services. A science-based assessment can help identify rivers in poor health and the likely causes of the decline in their ecological condition. This information can help prioritise government actions and funding aimed at improving river health, as well as assess the effectiveness of interventions. Reducing pollution and improving water quality and river health is currently a high priority for the Chinese government. Studies such as this one can support the government’s efforts by providing methods to better assess and understand the current ecological state of China’s rivers and the different factors that are affecting them.

River health monitoring is used to assess the current condition of an aquatic ecosystem as part of the process of maintaining or improving river health. This typically involves the development of health assessment indicators that reflect anthropogenic impacts and can be used to set minimum targets, which, if not met, are indicative of the need for management action.

The lower Yellow River study adopted a multi-metric approach, with indicators from the processes that force or drive ecological processes, and indicators of ecological response to these forces. In addition, the study included social river health indicators to measure the degree to which the river provided direct benefits to people living along the river. All indicators were scaled from 0 to 1, to allow easy comparison between indicators. Also, all indicators were based on a comparison with reference conditions, although the method for choosing reference was different for each indicator.

Indicator development work was undertaken for ecological, delta vegetation, water quality, hydrology, physical form and social indicators. The indicators were selected for their relevance to the lower Yellow River, some were based on existing methods, and some were developed specifically for the lower Yellow River but might have application elsewhere:

- the ecological indicators were based on standard methodologies used in other rivers
- water quality indicators and hydrology indicators were developed specifically for this project, but are expected to have wide application throughout China
- the delta vegetation indicator was specific to the lower Yellow River delta, but a similar approach could be taken to assessment of the health of any large-scale wetland assets
- the physical form indicators were specific to the peculiar geomorphological character of the lower Yellow River and were not intended for wider application, although it would be possible to use the indicators in any river with similar sediment and channel management issues
- the social indicators were selected for their relevance to the lower Yellow River, but they are expected to find application elsewhere in China.

The work undertaken for indicators of physical form and social river health should be regarded as preliminary. The physical form index was specific to the growth of the delta and, since sediment loads have fallen with the operation of Xiaolangdi Dam, the delta has been in a state of declining area, or risk of declining area. The social health indicators were the least developed of the indicators suggested in this report. Although preliminary, the data suggested a high level of social value provided by the river. Future work could fully develop the sub-index for characterising the recreational values provided by the ecological assets.

The combined indicator scores suggested that since the time of implementation of environmental flows on the river, particularly since 2004, hydrology has not been the main limiting factor to ecological health of the lower Yellow River. It appears more likely that water quality limits the ecological health. Application of the river health indicators to historical data clearly demonstrated the enormous improvements made to river water quality and hydrology since the late-1990s. It may take some time before the ecological response to improved hydrology and water quality is reflected in improved biotic health scores.
The methodology developed for this pilot study is open to improvement. The bioassessment for fish, macroinvertebrates and riparian plants could be improved by increasing the sampling effort.

It is necessary to recognise the challenge of making robust conclusions on river condition on the basis of a single investigation such as this. The natural variation in time and space of river health indicators represents an important constraint on river health assessments, especially when they are based on preliminary data sets, or those with limited spatial and temporal resolution. This study made use of historical data available for hydrology, water quality, and social values, and this helped to put the current state of river health into a historical perspective.

It was recommended that future work could refine the indicators, and in the case of physical form and social indicators, continue the development work. In the meantime, management actions that focus on water quality improvement and the continued refinement of the environmental flow regime, in accordance with the flow objectives identified in the environmental flows study, would also be expected to improve river health.

Care is required when transferring the results of this study to other rivers, because the lower Yellow River is unique in some respects. However, the suggested methods for calculating hydrological and water quality indicators in particular could be widely applied throughout China.
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### Acronyms

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<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ACEDP</td>
<td>Australia–China Environment Development Partnership</td>
</tr>
<tr>
<td>ARI</td>
<td>Average Recurrence Interval</td>
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<td>AusAID</td>
<td>Australian Agency for International Development</td>
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<tr>
<td>BI</td>
<td>Biological Index</td>
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<tr>
<td>CB</td>
<td>Contingent Behaviour</td>
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<td>CVM</td>
<td>Contingent Valuation Method</td>
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<tr>
<td>EC</td>
<td>Electrical Conductivity</td>
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<tr>
<td>EHMP</td>
<td>Ecosystem Health Monitoring Program</td>
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<tr>
<td>ETM</td>
<td>Enhanced Thematic Mapper</td>
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<tr>
<td>FCDRHYR</td>
<td>Flood Control and Drought Relief headquarter of Yellow River</td>
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<td>FFG</td>
<td>Functional Feeding Groups</td>
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<td>FSR</td>
<td>Flow Stress Ranking</td>
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<td>HD</td>
<td>Chinese Hydrology and Water Resources Index</td>
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<td>HFV</td>
<td>High-flow Volume</td>
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<td>HMF</td>
<td>Highest Monthly Flow</td>
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<td>IFD</td>
<td>Index of Flow Deviation</td>
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<td>IFH</td>
<td>Index of Flow Health</td>
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<tr>
<td>LFV</td>
<td>Low-Flow Volume</td>
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<tr>
<td>MWR</td>
<td>Ministry of Water Resources</td>
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<tr>
<td>LMF</td>
<td>Lowest Monthly Flow</td>
</tr>
<tr>
<td>PHF</td>
<td>Persistently Higher Flow</td>
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<tr>
<td>PLF</td>
<td>Persistently Lower Flow</td>
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<tr>
<td>PVL</td>
<td>Persistently Very Low</td>
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<tr>
<td>QA/QC</td>
<td>Quality Assurance/Quality Control</td>
</tr>
<tr>
<td>SAR</td>
<td>Synthetic Aperture Radar</td>
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<tr>
<td>SFCDRH</td>
<td>State Flood Control and Drought Relief Headquarters</td>
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<td>SFS</td>
<td>Seasonality Flow Shift</td>
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<tr>
<td>TCM</td>
<td>Travel Cost Method</td>
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<tr>
<td>TEV</td>
<td>Total Economic Value</td>
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<tr>
<td>TN</td>
<td>Total Nitrogen</td>
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<td>TP</td>
<td>Total Phosphorous</td>
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<tr>
<td>TSS</td>
<td>Total Suspended Solids</td>
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<tr>
<td>WSDDR</td>
<td>Water and Sediment Discharge Regulation</td>
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<td>YRCC</td>
<td>Yellow River Conservancy Commission</td>
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Chapter 1. Introduction

1.1 The importance of river health

‘River health’ is a concept that incorporates both ecological and human values. The health of a river depends on its ability to maintain its structure and function, to recover after disturbance, to support local biota, and to maintain key processes, such as sediment transport, nutrient cycling, assimilation of waste products, and energy exchange.

River health is important for people. Healthy rivers provide water for drinking, for agriculture, and for industry; fish and other produce for consumption; buffers against flooding; electricity generation; and transport and recreational opportunities. As rivers become unhealthy, they lose their capacity to provide these valuable goods and services. A healthy river is one that has the ability to sustain its ecological integrity and support a vibrant human community.

Maintaining and improving river health requires an accurate assessment of the current ecological state of river ecosystems. Ideally, this process should involve monitoring and assessment that can:

- identify those rivers that are in poor health, or at risk of poor health
- identify the likely causes of poor health, such as sources of pollution
- help prioritise funding for river restoration, including catchments that are most in need, and guide effective and efficient management actions
- assess the effectiveness of management actions, which can be particularly important where there is significant investment of public funds in improving river health
- allow for reporting on river health, to improve awareness within both government and the broader community of the current condition of a waterway.

River health monitoring can involve consideration of elements of a river ecosystem that respond at different spatial and temporal scales. These include water quality, the structure, abundance and condition of aquatic flora and fauna, hydrology, levels of catchment disturbance, and the physical form of the channel system. Importantly, no single variable can indicate ecological condition unequivocally and a suite of complementary variables is typically required to provide an accurate picture of river health. Water quality monitoring programs alone may over time prove inadequate in providing a thorough understanding of the condition of a river.

In recognition of the importance of healthy waterways, the Chinese government has committed to programs that will involve the investment of billions of dollars over coming decades to reduce pollution and to improve water quality and overall river health. A comprehensive program for river health monitoring and assessment has the potential to provide valuable guidance to these investments through the identification of priority regions for intervention, establishing effective and efficient management actions and strategies, and, by allowing for ongoing evaluation of the effectiveness of management, including pollution abatement and river rehabilitation actions.

The need for such a system is recognised in the ongoing efforts by various Chinese ministries and their agencies to improve the scope, quality and utility of information currently collected on river health. This report forms part of a project designed to contribute to that goal.

1.2 Background to this study

This report documents a component of a pilot study (‘the lower Yellow River pilot study’) undertaken as part of the River Health and Environmental Flow in China Project (‘the project’). The project is one of a number under the Australia-China Environment Development Partnership (ACEDP), an initiative of the Australian and Chinese governments, and funded through the Australian Agency for International Development. The study was also supported by funding from the Yellow River Conservancy Commission (YRCC), Ministry of Water Resources (MWR).

The project’s objective is to strengthen China’s approaches to improving river conditions through the development and application of advanced methods for monitoring river health and the estimation of environmental flows and policy approaches, with a broader aim to develop a consistent national approach to river health assessment. To this end, the project has involved the trial of international approaches to river health and environmental flow assessment as part of the three pilot studies conducted in the Pearl, Liao and Yellow River Basins (Figure 1).
River health assessments have been undertaken in all three pilot basins. The assessment methodologies applied in the three studies were similar, but not identical. The assessments involved analysis and interpretation of newly collected and existing data sources relevant to the health of the pilot sites. Based on the results of this work, the project commented on the current health of the pilot rivers, and recommended future monitoring programs and other management actions. The final stage of the project involves making recommendations – based on the results of the three pilot studies – about the options for developing and implementing a river health-monitoring program for wider use in China.

The lower Yellow River sub-project comprised two components: river health assessment, and environmental flows assessment. This report focuses on the river health assessment component. The environmental flows component was reported elsewhere (Gippel et al. 2012a; Gippel et al. 2012b).

1.3 Objectives of this report
In undertaking an integrated river health assessment, the objectives of the Yellow River pilot project were to:
- develop and demonstrate a method for assessing river health, suitable to Chinese conditions
- assess the relative ecological condition of the lower Yellow River
- assess the relative value of the social benefits provided by the lower Yellow River
- comment on the factors likely to be influencing river health and suitable policy responses
- demonstrate the use of a river health report card to summarise river health and convey that information in a clear and simple way
- assess the suitability of the assessment methodology for application in China
- make recommendations on the development of a river health-monitoring program for wider application within China.
Experience internationally shows that the process of developing a river health-monitoring program can take up to a decade and cost tens of millions of dollars. The work undertaken in this study is a modest, preliminary, but important step in that process.

It is challenging to make robust conclusions on river condition on the basis of an initial investigation. River health assessments make inferences about river health on the basis of what might be expected of a healthy river – such as the number of fish or macroinvertebrates, or the values of water quality parameters. The natural variation (in time and space) in these river health indicators represents an important constraint on river health assessments, especially when they are based on preliminary data sets, or those with limited spatial and temporal resolution. Establishing suitable reference values is a particular challenge when first implementing a monitoring program. Reference values typically need to be adapted from other regions, and refining them to accurately reflect the local conditions generally depends on the accumulation of additional data and an understanding of how they naturally vary. As a result, setting initial reference values for river health indicators is inherently difficult, and in the early stages of an investigation, reference values are likely to include a level of uncertainty.

The focus of the study, and its most significant outcome, was to establish a method for identifying suitable river health indicators and applying them, as well as starting the process of building a base of knowledge of the ecosystems of the lower Yellow River. The conclusions on the actual health of the river and recommended management responses that are made in this report are based on a limited, preliminary assessment. Therefore, the limitations of the study should be carefully considered when the results are used to inform management decisions. Over time, the outcomes of future river health assessments will improve as larger data sets become available, the local aquatic conditions are better understood, and reference values are refined.

1.4 Overview of the methodology and rationale

River health monitoring is used to assess the current condition of an aquatic ecosystem as part of the process of maintaining or improving river health. This typically involves the development of health assessment indicators, which reflect anthropogenic impacts and can be used to set minimum targets, which, if not met, are indicative of the need for some form of management action. While river health monitoring programs are somewhat unique to particular regions, based on local taxonomic and environmental characteristics, most have been developed around a similar conceptual foundation (see Gippel and Speed 2010). This approach involves the identification of a suite of indicators that describe the physical and biotic environment in ways that show a predictable response to anthropogenic drivers such as agricultural development and urbanisation. Indicators are typically used to assess condition by making comparisons against some form of reference condition – often the value an indicator would be expected to have in the absence of any form of human disturbance. By comparing scores for different rivers against some form of reference it is possible to rank locations in terms of their overall health. These rankings can then be used, generally together with some minimum acceptable level of health, to guide and prioritise investment to improve river health.

The river health assessment pilot studies undertaken on the Pearl River (International WaterCentre and Pearl River Water Resources Commission 2011) and the Liao River (International WaterCentre and Chinese Research Academy of Environmental Science 2011) differed significantly from the river health assessment undertaken on the lower Yellow River in three main respects:

1. The Pearl and Liao studies characterised the health of the stream network within whole sub-catchments (the Gui and Taizi River catchments, respectively), while the lower Yellow River pilot study was concerned only with the lowland mainstem of the Yellow River, which has very little local catchment (Figure 2).

2. The Pearl and Liao studies measured river health using in-stream biotic (fish, benthic macroinvertebrates and benthic algae) and water quality indicators, supported with some preliminary work on physical form and vegetation indicators. In contrast, the lower Yellow River pilot study adopted a holistic, multi-metric approach that integrated traditional bioassessment with physical form, vegetation, hydrology, water quality and social indicators.

3. The Pearl and Liao studies used catchment disturbance and hydrological alteration data to assist explaining patterns in the biotic and water quality indicators that were evident over the sub-catchments. The catchment disturbance gradient approach was not appropriate for the lower Yellow River, which is a linear system with a very small local catchment.
By sampling throughout catchments with varied land use and physiography, the Pearl and Liao studies were able to test indicators of ecosystem health against a disturbance gradient. The approach taken there was based on the successful and well-documented approach of the freshwater ecosystem health monitoring program (EHMP) in South East Queensland, Australia (Bunn et al. 2010). This approach focuses on using conceptual models and objective, quantitative testing of potential indicators against a known disturbance gradient. The approach involves eight distinct steps (Figure 3), which were described in the Liao and Pearl River pilot reports, and are not discussed in any detail here. The approach of Bunn et al. (2010) suits a situation where sampling is conducted throughout a catchment at sites that vary widely in terms of stream size, geomorphic type, upstream land use, local land use, disturbance intensity and type, altitude, climate and other factors. Also, a definite disturbance gradient should be present, and it is necessary to be able to locate and sample reference sites (minimally disturbed). While the approach can potentially be applied to rivers of any size, the focus on field sampling and comparison with reference sites is most appropriate to upland wadeable streams.

Compared to the network of relatively small and medium-sized streams situated within the Taizi and Gui River study areas of the Pearl and Liao pilots, the lower Yellow River study area could hardly be more contrasting. This is a single, mainstem length of a very large river channel (over 800 km long and ranging from a few hundred metres to two and a half kilometres wide), with relatively uniform physical and ecological character, relatively uniform local land use (and effectively the same upstream land use along its length), and no possibility of finding a reference site. In some respects, the lower Yellow River is unique in the world because:

- it was formerly the top-ranked river in the world for sediment load and sediment concentration and remains among the highest, yet it does not have a particularly high annual discharge
- the channel is contained within flood dikes or a nearby valley wall for its entire length
- a major flood with dike breach puts a population of 32.8 million at risk, 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 is highly vulnerable to floods, makes up 85 per cent of the lower river catchment area and has a population of 1.7 million residents living in 2,193 villages (mean density of 431 persons/km²) (Gippel et al. 2012a).
Although the lower Yellow River may be unique, the objective of this project was not to develop a unique method of river health assessment. The approach of the project was to adapt existing approaches where appropriate, and to develop new approaches, as necessary, with the potential to be applied to other large rivers that share some characteristics with the lower Yellow River. While some aspects of the framework set out in Figure 3 were not applicable to the lower Yellow River case, and some new elements were included, the framework was a useful basis for guiding development of the river health assessment program.

Two aspects of the approach taken to indicator selection in the lower Yellow River study strongly differentiated it from the Pearl and Liao studies: (i) the biological response indicators were integrated with indicators that characterised physical and chemical forcing variables (water quality, hydrology and physical form) and (ii) indicators of river-dependent social variables (response and forcing variables) were used to develop an index of social river health.

The forcing variables establish the conditions that allow ecological processes to proceed. In river health studies that focus on response variables, when otherwise positive forcing variables are impaired, they are often placed within the category of ‘threats’ to biotic integrity. For example, flowing water is the foundation for aquatic life in a river, but an impaired hydrological regime is a threat to achieving good ecological river health. Nutrients are an important food source to the biota of a river, but in oversupply they are regarded as pollution that threatens river health through eutrophication. While regular disturbance of the bed and banks is important for renewing physical habitats, if this proceeds at a rate outside the natural range it can seriously impair physical habitats.
There were two main reasons for including forcing variables together with response variables in the ecological river health index. The first reason is that data on forcing variables was plentiful, compared to ecological data. Sampling the ecology of a river the size of the lower Yellow River is a significant undertaking, and was considered beyond the resources of this pilot project. Fortunately, the YRCC had earlier commissioned the Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, to survey the ecology of the river in 2008, and these data were made available to the project. Although the value of this work to the project cannot be understated, relative to the size of the river, the sampling was of a modest scale (constituting only two sampling efforts – spring and autumn, 2008 – at only five sampling locations). In contrast, the YRCC established comprehensive monitoring programs for water quality, physical form and hydrology many years ago. The second reason for incorporating these forcing variables into the river health assessment was that they are the main river variables that are actively managed by YRCC. As a priority, YRCC is interested in developing methods for reporting progress in these management actions in a way that relates to, or demonstrates, river health outcomes.

The lower Yellow River is a working river, with millions of people directly dependent on its resources for their wellbeing, and dependent on control of its hydrology and physical form for their safety. The lives of these people are strongly tied to the operation of the river through the social and economic benefits they derive from the river’s resources. Throughout China, the Yellow River is known as the Mother River, which reflects the importance of its contribution to the emergence of the Chinese civilisation in the North China Plain. Today, the main social benefit provided by the lower Yellow River to local residents is its water, which is used to supply town, industrial and agricultural users, and to generate electricity. The way the river is managed can impact the reliability of water supply, and the suitability of the quality of water, for these purposes. Also, the way the lower Yellow River is managed impacts the risk of flooding, the consequences of which are potentially catastrophic in terms of loss of life, displacement of people, environmental damage, and economic cost. Social benefit is also derived from the ‘naturalness’ of the river, both for its intrinsic value and the economic benefit derived from nature-based tourism. YRCC is interested in developing methods for reporting the social health of the lower Yellow River, relative to river-related social benefits that are at least partly dependent on the way the river is managed.

The process undertaken in this study was designed to identify suitable indicators for incorporation into a routine monitoring program for the lower Yellow River. Once a monitoring program is established – which will require significant further work beyond that completed to date – some of the steps undertaken in this study should not need to be repeated on an annual basis. However, the program methodology should be subject to regular review and refinement as part of the cycle of adaptive management.
Chapter 2. Pilot Study Methodology

2.1 Step 1. Defining objectives for the program

In response to concerns about the deteriorating natural environment of the Yellow River, and declining quality of ecosystem services the river provided to society, Li (2004) formulated a policy framework for management of the Yellow River. 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 ‘ultimate target’, is:

- ‘Keeping the Yellow River Healthy’.

The vision encompasses both ecological health and social-economic health, which might 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 4 nos’:

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

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

1. Take measures to reduce sediment inflow to the Yellow River.
2. Manage effectively the water resources utilisation of the Yellow River basin and its related regions.
3. Strengthen the study on water transfer plans to increase the water resources of the Yellow River.
4. Establish water and sediment discharge regulation (WSDR) system.
5. Work out a scientific and reasonable general plan for the control and management of the lower river course.
6. Create favourable hydrological process to mitigate the shrinking of the main channel.
7. Meet water demands to maintain river itself cleaning capacity.
8. Carry out Yellow River delta management 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 to which the actions are applied
2. the ‘digital Yellow River’, which is the numerical simulation model of the natural, social and economic aspects of the river
3. the ‘scaled Yellow River’, which refers to physical models of the river used to simulate and experiment with particular natural phenomena or proposed actions.

The policy framework first announced by Li (2004) remains the fundamental guide to decision making for management of the Yellow River by the YRCC.

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 4 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, while in Li’s (2004) policy framework, ecosystem health was only an implicit target, apart from action 9, ‘Maintain the ecological system sustainable in the Yellow River delta’, which was specific to the delta only. Inclusion of 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. The five indicator categories listed by Liu et al. (2006), along with the policy framework of Li (2004), were used as a set of basic principles from which to develop environmental flow objectives and recommendations for the lower Yellow River (Gippel et al. 2012a). These principles also form the objectives of the river health assessment program, which are to:

- report on the degree of achievement of ‘the 4 nos’ (mainly social objectives), and
- report on how well the issues defined by the ‘Healthy Indicators of the Yellow River’ (incorporating social and environmental objectives) have been managed.

2.2 Step 2. Collating background information and development of conceptual models of river health

The task of collating background information about the lower Yellow River and developing conceptual models of river health was undertaken to jointly service the environmental flow and the river health components of the project. This review of literature and data was reported as *Environmental Flows Assessment for the Lower Yellow River: Site, Assets, Issues and Objectives* (Gippel et al. 2012a). While this was primarily intended as the knowledge foundation for the environmental flows assessment, but it was equally applicable to the river health assessment.

2.3 Step 3. Selection of potential indicators

The list of five ‘Healthy Indicators of the Yellow River’ set out by Liu et al. (2006) and ‘the 4 nos’ of (Li 2004) were translated into a set of key river health indicator groups (Figure 4). These groups fell into social and environmental types. Some of the key indicators comprised a number of sub-indicators that together formed the indicator. The indicator framework (Figure 4) does not imply equal weighting for the selected indicators. The relative importance of the indicators to the overall social and environmental indices depends on the relative importance placed on them by the YRCC, and the reliability of the method and data used to formulate the index value.

Figure 4. Key indicator groups and sub-indicators selected for the lower Yellow River health assessment pilot study. Social and environmental river health indicators

Note: Some sub-indicators comprised a number of components.
2.4 Step 4. Data collection and selection of suitable indicators

The approach taken in the Peal and Liao pilot studies was to use data collected at field sites located across the catchment to assess the suitability of potential indicators. The data were collected using standard methodologies used elsewhere in the world. The data were then used to derive values for a suite of indicators that were analysed against land-use disturbance gradients. A subset of indicators was then selected based on their effectiveness (i.e., response to the disturbance gradients) for inclusion in the report cards.

The situation in the lower Yellow River was different to that in the Pearl and Liao pilots because only one indicator group, the river channel ecological survey, involved project-specific field data collection. The ecological survey was undertaken in 2008, before the start of the ACEDP program. The survey used standard methods selected by scientists at the Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, who undertook the sampling. The process of selecting suitable indicators to represent the data was similar to that used in the Pearl and Liao pilots, except that the evaluation was not done with respect to a quantified environmental disturbance gradient, due to the small number of sampled sites and the shallow gradient of disturbance along the river. A number of considerations determined the choice of variables that were measured and the indices that were derived from the data:

- variables and indicators that have proven valuable in previous river health monitoring programs
- expert opinion
- experience of the project team
- local knowledge
- scientific literature
- skills of personnel undertaking the survey
- practicalities (e.g., budget, time, access) that determine what data can be collected in the field as well as analysed in the laboratory.

The other indicator groups used various pre-existing data. The assessment of vegetation health in the delta used remote sensing data, and it was necessary to develop indicators that characterised qualities of the delta that had been identified in conceptual models as being important (see Gippel et al. 2012a). In this case, the choice of variables and indicators was partly determined by technical limitations set by the remote sensing technology. The physical form, water quality and hydrology indicator groups all relied on data collected through well-established YRCC monitoring programs. The selection of indicators was conditioned by limitations imposed by the data, the management objectives that the indicators were intended to measure, and the way pre-existing standards required for ecological health were expressed (i.e., the indicators had to be compatible to allow testing of compliance with the standards).

The social indicator groups were selected on the basis of YRCC management opinion about priority concerns. The work on social indicators was preliminary and did not involve exhaustive testing of potential indicators. Rather, promising variables were selected on the basis of expert opinion, and most effort was expended in collecting relevant data and deriving simple indices that varied according to some aspect of river management.

The details about how data was collected and indicators were derived, are contained within the individual chapters about each indicator.

2.5 Step 5. River classification

When planning a catchment-scale river health assessment program, categorising similar types of rivers into groups is crucial for setting appropriate river health reference values, and ensures that comparisons are only made between comparable river types (Bunn et al. 2010). This process is based on dividing a catchment spatially based on its natural characteristics and is underpinned by the understanding that these characteristics influence aquatic ecosystem structure and function.

The lower Yellow River is essentially of the same natural geomorphic type along its entire length. The main difference in morphology (braided in the upper reaches to meandering in the lower reaches) has been imposed by river training works. Despite the relative uniformity of the river, consideration of the geomorphological and hydrological characteristics, and the location of the key ecological sets (see Gippel et al. 2012a) (Figure 2), established four reaches that were assessed separately. The same reaches were used for the environmental flows and river health assessments (Figure 5).
2.6 Step 6. Determination of reference values

River health reporting requires thresholds or target values for each indicator that reflect different levels of ecosystem health. Agreeing on levels that distinguish between ‘good’ condition (close to target or reference) and ‘poor’ condition (unacceptably distance from reference or target) is important.

Standards for water quality parameters are routinely set for different uses or values (e.g. aquatic biodiversity, drinking water, recreational contact, industrial use), which can be used to set thresholds of concern for water quality indicators. While the process of establishing targets and thresholds of concern (values for an indicator that are considered to reflect poor condition) can be guided by scientific knowledge of tolerances of biota, humans, and industrial and agricultural activities to certain parameters, this process also involves subjective decisions. Therefore, targets and thresholds may evolve over time, as well as vary from place to place. Different interest groups (e.g. tour operators, farmers, industry, conservationists) may have different perceptions about what is acceptable. Therefore, the final targets and thresholds may be arrived at partly via an iterative process involving some negotiation and assessment of different objectives.

River health programs often attempt to compare current stream condition against a ‘reference condition’ based on what values indicators would take if the site or catchment was undisturbed by human activity. In reality, true reference sites are hard to find except in undisturbed headwater streams. Alternatives for guideline values and reference conditions include:

- best attainable condition, i.e. the expected condition if BMP (best management practices) were in use, for a given use of the river or catchment
- established criteria or standards (often applied to water quality)
- standards required for designated use (swimming, fishing, industry, agriculture, drinking, e.g. China River Categories I-V)
- comparison with values derived from indicator-disturbance relationship equations (see Gippel and Speed 2010).

The lower Yellow River has been modified by humans for centuries, and clearly does not have undisturbed-type reference data available. In this case, an approach to reference was developed appropriate for each indicator group. In the case of hydrology, the reference was the standards specified by the environmental flow regime developed for the river by this project (Gippel et al. 2012a, 2012b). Water quality standards were based on literature review, analysis.

Figure 5. Lower Yellow River, showing four reaches used in river health (and environmental flow) assessment, location of gauging stations used for water quality and hydrological analysis, and location of ecological survey sites.
of historical water quality data, and a development of a conceptual understanding of the relationships between water quality parameter values and river health peculiar to the lower Yellow River. Physical form was evaluated against utilitarian management targets rather than ecological requirements, as the physical habitat requirements of the biota were largely unknown. The reference for ecological health was based on data from historical ecological surveys and experience from other large rivers in China. The reference for the social indicators was based on management targets.

2.7 Step 7. Assessment of condition and report card

Although river health assessment involves highly technical analysis, it is important that the results are communicated simply and effectively to different river interest groups. This can include government officials with different levels of technical training, other scientists, and also the wider community, who often have an interest in the health of local rivers. Ensuring effective communication to a diversity of groups may require several different forms of reporting. For the lower Yellow River, a detailed technical report (i.e. this report) describing the details of the methods and results was prepared together with a simple non-technical summary report. This technical report ensures that the methods can be repeated at a later time. The summary report was prepared in the style of a report card.

The report card aggregates scores for different indicators to give a simplified measure of health for the river. The aggregation process can involve averaging scores (i.e. assigning the same degree of importance to each indicator), or weighting scores (e.g. one indicator might be given greater value in calculating the overall site score, because of the importance of the indicator, or because it is more reliably measured). In the case of the lower Yellow River, both averaging and weighting approaches were used.

2.8 Step 8. Implementation of management responses

While one use of river health monitoring programs is to simply audit and report on the condition of ecosystems, the results can also guide investment in river health improvement. Decisions about whether to invest in management actions, and if so, which ones and where, are not strictly scientific ones. Rather, these decisions are guided by the desired state of the river based on the intended uses. The YRCC has a set of well-formulated management objectives, and the river health assessment was tailored to service those needs.
Chapter 3. Ecological Health – River Channel

The ecological component of the river health assessment for the lower Yellow River was undertaken principally by Liu Xueqin and Wang Hongzhu, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan (Liu and Wang 2010). This section of the report comprises edited extracts from Liu and Wang (2010). More details can be found in the original reports.

3.1 Background and rationale for inclusion

The bioassessment component of the lower Yellow River project was based on assessment of macroinvertebrates, fish, and riparian plants.

3.1.1 Benthic macroinvertebrates

Globally, stream macroinvertebrates are probably one of the most commonly used biological measures of stream health. For example, in Europe there are more than one hundred different bioassessment methods in use, and two-thirds of these methods are based on macroinvertebrates (Rosenberg and Resh 1993; Verdonschot et al. 2000). Macroinvertebrates are popular because they are found in most habitats, they have generally limited mobility, they are quite easy to collect by way of well established sampling techniques, and there is a diversity of forms that ensures a wide range of sensitivities to changes in both water quality (of virtually any nature) and habitats (Hellawell 1986).

Having collected benthic invertebrate samples, it is relatively straightforward to calculate a large number of different indices. Previous studies suggest these indices are frequently correlated with one another, and therefore a subset is generally sufficient for capturing the range of possible response patterns along gradients of disturbance (Bunn et al. 2010). The emphasis in adopting a final set of invertebrate indicators should be on selecting ones that show both predictable and consistent responses to the disturbance gradients, and which have a sound mechanistic explanation for such trends. A small number of reliable indicators with these properties will be far more effective than a longer list of less reliable or defensible ones.

3.1.2 Fish

Fish have valuable properties as an indicator group because, as well as having a range of sensitivities to water quality and habitat degradation, they are relatively easy to sample and identify in the field, and they tend to integrate the effects of lower trophic levels. Therefore, fish assemblage structure is reflective of integrated environmental health (Barbour et al. 1999; Kennard et al. 2001). As they typically move over larger spatial scales and are comparatively long-lived, fish are also suited to assessing macro-habitat and regional differences, and integrating the effects of long-term changes in stream health (Kennard et al. 2001). Fish are also highly valued socially and economically, so there is often a strong desire by the community and management agencies to incorporate them into river health assessment programs. Nonetheless, there are specific challenges that arise in relation to sampling of fish.

While fish are easily identified in the field, typically a high sampling effort is required to provide consistent measures of abundance and community composition (e.g. Kennard et al. 2001). In addition, differences in stream size will typically necessitate different sampling approaches. These issues can be problematic in terms of calculating indices based on abundance, biomass or species richness, all of which are obviously sensitive to sampling effort. There is a number of alternative indicator types that have been applied to fish assemblages, such as the proportion of introduced or migratory species, and changes in the relative number of pollution sensitive taxa (e.g. fish IBI of Barbour et al. 1999). However, with the exception of exotic species, these indicators depend on the development of expected (reference) values that may be difficult to develop unless historical data can be accessed.

3.1.3 Riparian plants

Riverine vegetation includes plants in the river channels and riparian zone, which includes river banks, the floodplain and its wetlands, and other fluvial landforms inundated by bankfull discharge (Hupp and Osterkamp 1996). Reflecting the broad range of environmental conditions (Richardson et al. 2007), riverine flora is typically very diverse (Hughes 1997; Naiman and Décamps 1997). Whether herbs, shrubs or trees, all riverine vegetation provides an important role for both the structure and function of river ecosystems (Barling and Moore 1994; Naiman and Décamps 1997; Pen 1999; Richardson et al. 2007). The services that riverine plants provide are crucial for ecosystem health and are highly valuable to humans. These include:

- **Habitat:** Living and dead vegetation provides habitat for other biota. For example, it acts as a substrate for algae and invertebrates, and it can create pools and backwaters of low velocity suitable for fish and turtles.

- **Source of energy and nutrients:** In-stream and riparian vegetation provide a source of carbon, nutrients and energy, and helps to form the basis of aquatic (and terrestrial) food webs.

- **Water filtration:** Riparian vegetation provides a buffer zone that filters sediments and controls nutrients. In-stream vegetation acts like a sewage treatment plant by filtering water and improving its quality.
• Channel and river-bank stabilisation: Shoots and particularly roots of riverine vegetation stabilise stream channels and banks.
• Dispersal corridors: Intact strips of riparian vegetation provide a corridor for the movement of animals.
• Moderation of stream temperature: Vegetation can moderate stream water temperature through evapotranspiration and shading.

The health of riverine vegetation is threatened by numerous processes that occur both inside and outside of the actual river. Threats to riverine vegetation include:
• hydrological modification
• water pollution and disturbance caused by recreation and navigation along the river
• catchment land use practices that lead to vegetation clearing, livestock grazing and trampling, water pollution (including eutrophication) and increased sediment deposition
• invasion by alien plants that can reduce native plant cover and diversity and alter the structure and function of riparian plant communities.

Riparian vegetation provides numerous ecosystem services and functions, so disturbance and loss of riparian vegetation can impede river health. Assessing the condition of riparian vegetation can indicate the extent of human modification and disturbance that a riverine ecosystem has experienced and it also indicates the relative health of the riparian ecosystem.

3.2 Methodology

3.2.1 Field survey

Two biological surveys were carried out in the spring (April–June) and the autumn (September–October) in 2008. Three river locations were sampled during spring, i.e. Huayuankou, Gaocun, and Lijin. Two additional river locations, Aishan and the delta, were included in the autumn survey (Figure 5). All sampling sites were located nearby local hydrological stations.

Environmental parameters that were measured at the time of sampling included water depth, Secchi depth, flow velocity, pH, conductivity, TN and TP using standard methods (Huang, 1999). Fish, macroinvertebrates and riparian plants were also sampled (Table 1).

Table 1. Number of samples taken for each parameter during two surveys.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Number of samples (spring survey/autumn survey)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Huayuankou</td>
</tr>
<tr>
<td>Environmental parameters</td>
<td>3/9</td>
</tr>
<tr>
<td>Riparian plants</td>
<td>8/13</td>
</tr>
<tr>
<td>Macroinvertebrates</td>
<td>4/6</td>
</tr>
<tr>
<td>Fish</td>
<td>1/1</td>
</tr>
</tbody>
</table>

Fish samples were collected using gill nets and casting nets. Samples were also collected from the fish catch of fishers and local markets. Local residents and local fishery management organisations were consulted regarding local fishery information. All specimens were identified, measured and weighed. Fishes were identified according to taxonomic monographs (Chen et al. 1998; Chu et al. 1999; Yue et al. 2000; Zhu 1995).

Benthic macroinvertebrates were collected with a modified Peterson grab sampler (1/16 m²) and cleaned gently with a 425 μm sieve. Animals were sorted in the laboratory and cleaned with distilled water before preservation in 10 per cent formalin. All specimens were identified to species, or to genus whenever the species was indeterminate according to taxonomic monographs (Brinkhurst and Jamieson 1971; Epler 2001; Liu et al. 1979; Morse et al. 1994; Wang 2002). Animals were also collected by a hand net as qualitative supplements.

Riparian plant data were collected at each sampling site by counting the total number of species over a transect set perpendicular to the main channel. Transect length varied with the width of the riparian zone, but most were less than 500 m long. Also, quantitative samples were collected from 3–13 1 m² plots located along the transects. The number of plots was proportional to the complexity of the riparian landform. Plants were identified, counted and weighed. Species were identified using standard keys (Fu 2002; Li 2005; Ma 2003; Diao 1983; Zhao 2001).
3.2.2 Aggregating data

Functional zones

The four reaches classified by geomorphological and hydrological character (Figure 5) were also adopted as ecological functional zones:

- Reach (Zone) 1. Two types of habitat were observed in this reach: (i) main channel with small area of bottomland and (ii) large area of wetland (in Huayuankou). Only one site (Huayuankou) was sampled during the 2008 survey.
- Reach (Zone) 2. One type of habitat was observed in this reach: main channel with small area of bottomland. There were two sampling sites in this zone: Gaocun and Aishan.
- Reach (Zone) 3. One type of habitat was observed in this reach: main channel with small area of bottomland. There was one sampling site in this zone: Lijin.
- Reach (Zone) 4. The reach containing the delta was observed to contain a complex range of habitats: the main channel, river anabranches, large area of wetlands, and permanent waterbodies (such as small lakes and reservoirs). Only one site (in the delta) was sampled during the 2008 survey.

Fish

Fish data from the two surveys in 2008 were combined as a single data set. Presence/absence, native/exotic, feeding guilds and habitat guilds were identified. Abundance and body size data were unavailable for most fishes.

Macroinvertebrates

Macroinvertebrate data from the two surveys in 2008 were combined as a single data set. Presence/absence, functional feeding groups (FFG), densities and biomasses, and tolerance values were determined.

Riparian plants

Riparian plant data from the two surveys in 2008 were combined as a single data set. Presence/absence, grass/woody species, salt tolerant species, and biomasses were determined.

3.2.3 Determination of reference

Fish

The reference condition of fish in the lower Yellow River was reconstructed on the basis of historical data, literature and expert knowledge. Two historical surveys of fish in the river were undertaken in 1958 and 1980. However, the data were incomplete, and only presence/absence information was available. A complete list of fish species that can potentially be present in the lower Yellow River was constructed by collecting information from a large number of publications, documents, websites (www.fishbase.org) and expert opinion. Species expected to be present in the lower Yellow River were first listed. Then extinct species and marine fishes were excluded. The list was then reviewed by experts (Dr. Li Xiuqi from Shandong Fisheries Research Institute and Mr. Ru Huijun from the Institute of Hydrobiology, CAS). The final species list was assumed to indicate the maximum potential taxonomic diversity of fish in the 1950s. However, this is not the same as the diversity expected for a single sampling effort, which would be lower.

Macroinvertebrates

The reference condition of benthic macroinvertebrates in the lower Yellow River was reconstructed on the basis of historical data, literature and expert opinion. A few studies were available from the delta (Jia and Tian 2003; Zhang et al. 1990; Zheng et al. 2010), but there was no information available from the other reaches. Also, only presence/absence data were available from these publications. Reference condition for macroinvertebrates was reconstructed assuming that species richness was positively correlated with habitat diversity. It was also assumed that species richness was proportional to the number of different habitat types available. Historical data from the delta was used to estimate the species richness of other reaches, by comparing the availability of habitats in those reaches. For example, there are four types of habitats and 69 freshwater species in reach 4, while only one habitat type in reach 2; therefore, the species richness in reach 2 was estimated by $1/4 \times 69 = 17$. The coarseness of this reference estimation method is acknowledged, but was unavoidable given the lack of an alternative. This method was also used to estimate the expected density of macroinvertebrates in the lower Yellow River. The densities were determined according to the densities of macroinvertebrates found in similar habitats in other rivers and waterbodies (Zhao, 2010; unpublished data). The macroinvertebrate reference data were assumed to represent the maximum potential taxonomic diversity that prevailed in the late-1980s to early-1990s.

Riparian plants

A large number of studies have been undertaken on plants of the lower Yellow River, especially in the delta region (e.g. Duan et al. 2008; Song, 2005; Zhang et al. 2006). The reference conditions of plants were determined according to historical records. However, only species richness data were available. The historical data were limited to information on species richness. The riparian plant reference data were assumed to represent the maximum potential taxonomic diversity that prevailed in the early-2000s.
3.2.4 Ecological indices

The ecological indices were determined using the 2008 survey data and historical records. Potential indices that could be calculated from the dataset were listed, and then evaluated on the basis of their simplicity of understanding, relevance to the lower Yellow River, information content, and sensitivity. There were insufficient data points to relate the patterns to an environmental disturbance gradient.

3.2.5 Procedure for calculating river health score

Based on the observed/expected (O/E) dataset, ecosystem health was assessed for each river reach by calculating the scores for each index. For example, 31 fish species were observed in reach 1, and the expected species in reach 1 was estimated to be 83, so the O/E score for species richness was calculated as 31/83 = 0.37. This method gave a score for each index in the range 0–1, with higher values indicating ecological conditions closer to reference. The final score for the lower Yellow River was calculated according to a series of weightings (Figure 6).

Figure 6. Procedure to derive indicator group index scores and reach index scores from ecological data.

All potential species cannot be sampled in one or two survey efforts. Many studies have shown that abundance and diversity continue to increase up to a given sampled area (e.g. Colwell and Coddington 1994; Connor, et al. 2000; Gotelli and Colwell 2001; van Gemerden et al. 2005). In a comprehensive river health survey, a first step is to establish the relationship between the value of the chosen index score and the level of sampling effort to determine the level at which the sampling effort of the index value stabilises. At this point, the survey data represents the true community diversity rather than just being a consequence of the level of sampling effort. The 2008 ecological river health survey on the lower Yellow River was the first such survey and should be considered preliminary. Standard sampling procedures were employed, but the efficiency of the level of sampling effort was not evaluated. This sampling effort issue applies more to fish than it does to macroinvertebrates and plants. Therefore, the scores calculated from this survey would likely underestimate fish species diversity, but no data were available on which to base an adjustment to the raw data. However, an adjustment was made for relative efficiency of the sampling effort (data quality weighting in Adapted from Liu and Wang (2010).)

Figure 6) by weighting the fish score lower than those for plants and macroinvertebrates when calculating the combined ecological health score.
### 3.3 Results

#### 3.3.1 Observed versus expected for potential indices

The observed and expected values of indices for fish (Table 2), riparian plants (Table 3) and macroinvertebrates (Table 4) were determined for the four reaches of the lower Yellow River. The expected values are equivalent to the highest possible historical reference condition. For plants, some expected values were unavailable due to lack of data. For macroinvertebrates, the reference condition was determined for several indices, i.e. total species richness, number of FFGs and total density. Expected values for other indices were unavailable due to lack of historical data.

#### Table 2. Observed and expected reference index values for fish in the four reaches of the lower Yellow River.

<table>
<thead>
<tr>
<th>Index groups</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reach</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 2 3 4</td>
<td>1 2 3 4</td>
</tr>
<tr>
<td>Total species (No.)</td>
<td>31 12 6 17</td>
<td>83 83 83 108</td>
</tr>
<tr>
<td>Piscivores (No.)</td>
<td>8 0 1 4</td>
<td>12 9 9 15</td>
</tr>
<tr>
<td>Carnivores (No.)</td>
<td>10 4 3 5</td>
<td>33 34 34 45</td>
</tr>
<tr>
<td>Omnivores (No.)</td>
<td>7 6 2 6</td>
<td>26 29 29 33</td>
</tr>
<tr>
<td>Herbivores (No.)</td>
<td>6 2 0 2</td>
<td>12 11 11 15</td>
</tr>
<tr>
<td>Total migratory species (No.)</td>
<td>8 0 1 6</td>
<td>13 16 16 26</td>
</tr>
<tr>
<td>Migratory species (Freshwater-Marine)</td>
<td>2 0 0 3</td>
<td>3 7 7 19</td>
</tr>
<tr>
<td>Migratory species (Freshwater-Freshwater)</td>
<td>6 0 1 3</td>
<td>10 9 9 7</td>
</tr>
<tr>
<td>Non-migratory species (No.)</td>
<td>23 12 5 11</td>
<td>70 67 67 82</td>
</tr>
<tr>
<td>Freshwater and Brackish species (No.)</td>
<td>3 1 0 3</td>
<td>4 8 8 30</td>
</tr>
<tr>
<td>Brackish only (No.)</td>
<td>0 0 0 0</td>
<td>0 0 0 11</td>
</tr>
<tr>
<td>Freshwater only (No.)</td>
<td>28 11 6 14</td>
<td>79 75 75 67</td>
</tr>
<tr>
<td>Exotic (No.)</td>
<td>1 0 0 0</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td>Native (No.)</td>
<td>30 12 6 17</td>
<td>82 82 82 107</td>
</tr>
</tbody>
</table>

#### Table 3. Observed and expected reference index values for riparian plants in the four reaches of the lower Yellow River.

<table>
<thead>
<tr>
<th>Index groups</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reach</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 2 3 4</td>
<td>1 2 3 4</td>
</tr>
<tr>
<td>Total Species (No.)</td>
<td>66 69 53 35</td>
<td>149 149 149 193</td>
</tr>
<tr>
<td>Woody species (No.)</td>
<td>2 3 2 1</td>
<td>9 9 9 6</td>
</tr>
<tr>
<td>Grass species (No.)</td>
<td>64 66 51 34</td>
<td>140 140 140 187</td>
</tr>
<tr>
<td>Salt tolerant plants (No.)</td>
<td>9 8 10 12</td>
<td>73</td>
</tr>
<tr>
<td>Non tolerant plants (No.)</td>
<td>57 61 43 23</td>
<td>120</td>
</tr>
<tr>
<td>Density of grass species (individuals/m²)</td>
<td>145.0 59.0 16.0 87.0</td>
<td>73</td>
</tr>
<tr>
<td>Biomass of grass species (g/m²)</td>
<td>1722.4 137.7 209.5 1022.4</td>
<td>120</td>
</tr>
</tbody>
</table>
3.3.2 Selection of suitable ecological indices

A number of ecological indices were selected for inclusion in the river health assessment (Table 5). Total species richness is the most important index for all ecological groups because it represents information on total biodiversity. This was the only index selected for riparian plants.

Five indices were selected for fish. With regard to trophic structure, top predators are widely regarded as keystone species in freshwater ecosystems; therefore, piscivore species richness was selected as an index. Migratory species richness was also selected, because it can be used to assess the impact of barriers, whether physical, hydraulic or chemical. Considering that both brackish and freshwater species occurred in reach 4 (the delta), the freshwater species richness was used as an index in this reach. Native species richness was also selected to show the effects of exotic species.

Three indices were determined for macroinvertebrates – total species richness, number of FFGs and total density. These represented the total biodiversity, functional biodiversity, and productivity respectively.
Table 4. Observed and expected reference index values for macroinvertebrates in the four reaches of the lower Yellow River.

<table>
<thead>
<tr>
<th>Indices</th>
<th>Groups</th>
<th>Observed Reach</th>
<th>Expected Reach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Number of taxa</td>
<td>Total species</td>
<td>28</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Oligochaetes</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Molluscs</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Aquatic insects</td>
<td>18</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Other animals</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>FFGs</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Predators</td>
<td>6.7</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Collector-gatherers</td>
<td>12.8</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>Collector-filterers</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Scrapers</td>
<td>5.7</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Shredders</td>
<td>2.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Number of FFGs</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Density(individuals/m²)</td>
<td>Total</td>
<td>432.0</td>
<td>110.0</td>
</tr>
<tr>
<td></td>
<td>Oligochaetes</td>
<td>26.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Molluscs</td>
<td>0.0</td>
<td>14.4</td>
</tr>
<tr>
<td></td>
<td>Insects</td>
<td>382.0</td>
<td>85.6</td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>24.0</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td>FFGs</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Predators</td>
<td>100.7</td>
<td>11.7</td>
</tr>
<tr>
<td></td>
<td>Collector-gatherers</td>
<td>214.3</td>
<td>40.6</td>
</tr>
<tr>
<td></td>
<td>Collector-filterers</td>
<td>2.7</td>
<td>14.4</td>
</tr>
<tr>
<td></td>
<td>Scrapers</td>
<td>2.7</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Shredders</td>
<td>103.7</td>
<td>48.3</td>
</tr>
<tr>
<td>Biomass(g/m²)</td>
<td>Total</td>
<td>1.414</td>
<td>0.706</td>
</tr>
<tr>
<td></td>
<td>Oligochaetes</td>
<td>0.176</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Molluscs</td>
<td>0.000</td>
<td>0.052</td>
</tr>
<tr>
<td></td>
<td>Insects</td>
<td>0.134</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>1.104</td>
<td>1.278</td>
</tr>
<tr>
<td></td>
<td>FFGs</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Predators</td>
<td>0.050</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Collector-gatherers</td>
<td>0.222</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>Collector-filterers</td>
<td>0.003</td>
<td>0.051</td>
</tr>
<tr>
<td></td>
<td>Scrapers</td>
<td>0.003</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Shredders</td>
<td>1.133</td>
<td>0.646</td>
</tr>
<tr>
<td>BI</td>
<td>Hilsenhoff BI</td>
<td>6.5</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>Shannon Wiener (H')</td>
<td>1.5</td>
<td>0.7</td>
</tr>
</tbody>
</table>

FFG is a functional feeding group. BI is biological index.
Table 5. Ecological indices selected for inclusion in the lower Yellow River health assessment.

<table>
<thead>
<tr>
<th>Fish</th>
<th>Macroinvertebrates</th>
<th>Riparian plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total species ($S_f$)</td>
<td>Total species ($S_m$)</td>
<td>Total species ($S_p$)</td>
</tr>
<tr>
<td>Piscivore species ($P$)</td>
<td>Number of FFGs ($FFG$)</td>
<td></td>
</tr>
<tr>
<td>Migratory species ($M$)</td>
<td>Total density ($p$)</td>
<td></td>
</tr>
<tr>
<td>Freshwater species ($F$)</td>
<td>(Reach 4 only)</td>
<td></td>
</tr>
<tr>
<td>Native species ($N$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.3.3 Ecological river health score

The final scores for each ecological group of fish ($F$); macroinvertebrates ($M$); and riparian plants ($P$) were weighted by relative importance of the indices (Table 6). With regard to fish, total species richness was considered the most important measure of overall health and was given the highest weight. Richness of native species was given the lowest weight because, with only one exotic species expected and recorded in the lower Yellow River, this index gave values close to that of total species richness. Indices of richness of migratory and piscivore species were given mid-level weights, except in reach 4 (estuary), where migration was less important. For macroinvertebrates, total species richness, FFGs and density were given weights of 0.4, 0.1 and 0.5. Both total species richness and FFGs represent information of biodiversity, and density provides information of productivity. In this way, the two types of indices (i.e. biodiversity and productivity) were equally weighted.

Table 6. Equations used to weight the indices and calculate the final score for the lower Yellow River ecological health assessment.

<table>
<thead>
<tr>
<th>Indicator Group</th>
<th>Reach</th>
<th>Index score equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish</td>
<td>Reach 1</td>
<td>$F_1 = Q_{f1} (0.5S_f + 0.2P + 0.2M + 0.1N)$</td>
</tr>
<tr>
<td></td>
<td>Reach 2</td>
<td>$F_2 = Q_{f2} (0.5S_f + 0.2P + 0.2M + 0.1N)$</td>
</tr>
<tr>
<td></td>
<td>Reach 3</td>
<td>$F_3 = Q_{f3} (0.5S_f + 0.2P + 0.2M + 0.1N)$</td>
</tr>
<tr>
<td></td>
<td>Reach 4</td>
<td>$F_4 = Q_{f4} (0.5S_f + 0.2P + 0.2M + 0.1N)$</td>
</tr>
<tr>
<td>Macroinvertebrates</td>
<td>Reach 1</td>
<td>$M_1 = Q_{m1} (0.4S_m + 0.1FFG + 0.5p)$</td>
</tr>
<tr>
<td></td>
<td>Reach 2</td>
<td>$M_2 = Q_{m2} (0.4S_m + 0.1FFG + 0.5p)$</td>
</tr>
<tr>
<td></td>
<td>Reach 3</td>
<td>$M_3 = Q_{m3} (0.4S_m + 0.1FFG + 0.5p)$</td>
</tr>
<tr>
<td></td>
<td>Reach 4</td>
<td>$M_4 = Q_{m4} (0.4S_m + 0.1FFG + 0.5p)$</td>
</tr>
<tr>
<td>Riparian plants</td>
<td>Reach 1</td>
<td>$P_1 = Q_{p1} (1.0S_p)$</td>
</tr>
<tr>
<td></td>
<td>Reach 2</td>
<td>$P_2 = Q_{p2} (1.0S_p)$</td>
</tr>
<tr>
<td></td>
<td>Reach 3</td>
<td>$P_3 = Q_{p3} (1.0S_p)$</td>
</tr>
<tr>
<td></td>
<td>Reach 4</td>
<td>$P_4 = Q_{p4} (1.0S_p)$</td>
</tr>
</tbody>
</table>

The scores for each river reach were calculated by combining the three ecological indices. For each ecological group, the score was weighted by data quality (Table 7). In reaches 1 to 3, macroinvertebrates and plants were given the same weightings (0.4) because they were both taken with what were considered adequate sampling efforts. Fish were given a lower weighting (0.2) because the sampling effort was insufficient to fully characterise the diversity. In reach 4 (estuary), plants were given a higher weighting (0.6), and both fish and macroinvertebrates were given lower values (0.2) due to relatively poor sampling efforts.

The final scores for the river reaches (Table 8; Figure 7) indicated a degraded river health condition relative to the reference used here. The ecological condition of reach 1 was the closest to reference, followed by reach 2, reach 3 and reach 4 in that order. Reach 4 scored relatively low in each indicator, which is explained by the higher reference standards for the delta. Historically, the delta (reach 4) had a high biodiversity, but the sampling in 2008 observed lower diversity relative to this standard. Also, the numbers of species observed in the delta (reach 4) were lower than observed in reach 1, even though reach 1 had a lower expected diversity. These results should be regarded as preliminary, as further sampling of more areas of the delta might reveal higher diversity of biota than recorded in the 2008 survey.
Table 7. Data quality weightings used to calculate the ecological river health score for the lower Yellow River ecological health assessment.

<table>
<thead>
<tr>
<th>Indicator Group</th>
<th>Reach 1</th>
<th>Reach 2</th>
<th>Reach 3</th>
<th>Reach 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish</td>
<td>$Q_f^1 = 0.2$</td>
<td>$Q_f^2 = 0.2$</td>
<td>$Q_f^3 = 0.2$</td>
<td>$Q_f^4 = 0.2$</td>
</tr>
<tr>
<td>Macroinvertebrates</td>
<td>$Q_m^1 = 0.4$</td>
<td>$Q_m^2 = 0.4$</td>
<td>$Q_m^3 = 0.4$</td>
<td>$Q_m^4 = 0.2$</td>
</tr>
<tr>
<td>Riparian plants</td>
<td>$Q_p^1 = 0.4$</td>
<td>$Q_p^2 = 0.4$</td>
<td>$Q_p^3 = 0.4$</td>
<td>$Q_p^4 = 0.6$</td>
</tr>
</tbody>
</table>

Table 8. Ecological index scores for each reach in the lower Yellow River.

<table>
<thead>
<tr>
<th>Indices</th>
<th>Reach 1</th>
<th>Reach 2</th>
<th>Reach 3</th>
<th>Reach 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Species</td>
<td>0.37</td>
<td>0.14</td>
<td>0.07</td>
<td>0.16</td>
</tr>
<tr>
<td>Piscivores species</td>
<td>0.67</td>
<td>0.00</td>
<td>0.11</td>
<td>0.27</td>
</tr>
<tr>
<td>Migratory species</td>
<td>0.62</td>
<td>0.00</td>
<td>0.06</td>
<td>0.23</td>
</tr>
<tr>
<td>Freshwater species</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.21</td>
</tr>
<tr>
<td>Native species</td>
<td>0.37</td>
<td>0.15</td>
<td>0.07</td>
<td>0.16</td>
</tr>
<tr>
<td>Weighted group score</td>
<td>0.48</td>
<td>0.09</td>
<td>0.08</td>
<td>0.19</td>
</tr>
<tr>
<td>Macroinvertebrates</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total species</td>
<td>0.81</td>
<td>0.70</td>
<td>0.29</td>
<td>0.03</td>
</tr>
<tr>
<td>Number of FFGs</td>
<td>1.00</td>
<td>1.00</td>
<td>0.60</td>
<td>0.20</td>
</tr>
<tr>
<td>Density</td>
<td>0.62</td>
<td>0.28</td>
<td>0.72</td>
<td>0.30</td>
</tr>
<tr>
<td>Weighted group score</td>
<td>0.73</td>
<td>0.52</td>
<td>0.53</td>
<td>0.18</td>
</tr>
<tr>
<td>Riparian plants</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total species</td>
<td>0.44</td>
<td>0.46</td>
<td>0.36</td>
<td>0.18</td>
</tr>
<tr>
<td>Group score</td>
<td>0.44</td>
<td>0.46</td>
<td>0.36</td>
<td>0.18</td>
</tr>
<tr>
<td>Combined score</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weighted combined indicator score</td>
<td>0.564</td>
<td>0.410</td>
<td>0.372</td>
<td>0.182</td>
</tr>
</tbody>
</table>
Figure 7. Ecological river health index scores for the four reaches of the lower Yellow River for 2008.
Chapter 4. Ecological Health – Delta Vegetation

The delta vegetation component of the river health assessment for the lower Yellow River was undertaken principally by Chen Liang, Yellow River Conservancy Commission, Zhengzhou (Chen, 2010). This section of the report comprises edited extracts from Chen (2010). More detailed information can be found in the original report.

4.1 Background and rationale for inclusion

Vegetation is perhaps the most conspicuous feature of wetland ecosystems and has been used extensively as an indicator of wetland health and to define wetland boundaries. Vegetation plays important roles in the maintenance of wetland ecosystems, including:

- being the base of the food chain, vegetation is a primary pathway for energy flow in the system, and provides food for birds, fish and insects
- vegetation provides important physical habitats for birds, fish and insects
- vegetation has the capacity to improve water quality through the uptake of nutrients, metals, and other contaminants
- by influencing hydraulics, vegetation impacts the hydrological and sediment regimes, including being a major determinant of mudflat and shoreline stability (U.S. EPA 2002; Johansen and Phinn 2006).

The lower Yellow River Delta contains internationally important wetlands, and the ecological value of these wetlands is heavily dependent on the health of vegetation communities (see Gippel et al. 2012a). Management of environmental flows to the delta is mainly driven by vegetation objectives, so assessment of vegetation health in the delta is a priority issue.

Traditional field survey methods provide a great deal of detail at the local site- and species-scale, but small plots are less useful for mapping the extent of vegetation communities over wide areas. The alternative technology in this case is remote sensing. Previous studies have demonstrated that images with medium spatial resolution, such as Landsat TM (Thematic Mapper) and Landsat ETM+ (Enhanced Thematic Mapper plus), were suited to mapping the extent of riparian zones greater than 50 m wide but performed poorly where the riparian strip was narrow (Congalton et al. 2002; Johansen and Phinn 2006). High-resolution images allow mapping of vegetation properties other than extent, such as leaf area index, canopy percentage foliage cover, and vegetation species (e.g. Davis et al. 2002; Johansen and Phinn 2006; Alencar-Silva and Maillard 2010). However, routine assessment of vegetation health using remote sensing technology remains a challenge due to the lack of a standard approach.

The objectives of this study are to:

- assess the suitability of Landsat TM/ETM+ satellite data to generate indices of wetland vegetation health
- develop a remote sensing method for assessment of wetland vegetation health that can be applied to the lower Yellow River delta
- measure indices of wetland vegetation health for the lower Yellow River delta.

4.2 Study area

The Yellow River delta (Figure 8) is unique among global wetland systems because of its historically rapid rate of progradation, driven by the extremely high sediment load of the Yellow River. The modern delta developed since 1855 and, over that time, it has shifted course more than 50 times, with eight to twelve shifts 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.

The rapid rate of progradation of the delta has allowed a high rate and extent of vegetation succession, which in turn has provided the area with a high conservation value for waterbirds, as well as fish and macroinvertebrates (see Gippel et al. 2012a). However, with an increase in human activities and significant decrease in flow from the Yellow River (Gippel et al. 2012a), degradation of the ecosystem of the delta has been documented, especially from the late-1990s. To protect the globally important wetland habitats, restoration activities involving the artificial delivery of 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 × 10^6 m³ of freshwater has been pumped annually from the river 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) (Figure 8). Consequently, hydrological conditions, salinity, and vegetation communities have been restored to that area (Li et al. 2011).
Reed (Phragmites australis), Tamarisk (Tamarix chinensis shrubland and woodland communities) and Suaeda (Suaeda salsa saltmarsh community) (Figure 9) are the three main natural vegetation communities in the delta (Figure 8). The Tamarisk community helps to prevent sea-water intrusion in coastal areas of northern China (Cui et al. 2010), while Reed is the constructive species of most wetland plant communities in the delta (Cui et al. 2008). The constructive species is the species with the highest biomass production that builds up the vegetation coverage and aids the development and persistence of the vegetation community. Tamarix chinesis and Suaeda salsa are distributed in areas that contain higher soil salt content, while Phragmites australis is mainly distributed in areas with plentiful fresh water around the shoreline of the Yellow River, along the abandoned course of the Yellow River, and in a restored wetland area (Figure 8).

As well as being affected by altered hydrology and sediment load, the delta environment has been impacted by soil salinisation and land reclamation (see Gippel et al. 2012a). Land reclamation converted large areas of former wetland vegetation into farmland. In some cases, the appropriated land was later abandoned due to salinisation and loss of soil fertility, and the land then reverted back to a more natural state. Based on the history of land use change and water management, three indicator groups were considered appropriate to the management issues identified at the delta:

- composition of the three main plant communities: Reed, Tamarisk and Suaeda
- extent of farmland
- rate of estuary growth.

The southern, currently fluvially active, area of the Yellow River Delta National Nature Reserve (Figure 8) was the focus area of this study. Multi-temporal historical Landsat TM/ETM+ images were used to survey the conditions of vegetation composition, farmland and estuary growth.
Figure 9. The three main plant communities of the lower Yellow River.

Photographs supplied by Chen Liang (YRCC).
4.3 Previous investigations

The area of various land use, wetland and vegetation categories of the Yellow River Delta have been previously investigated using remote sensing technologies. One reason for apparent differences between studies in the relative composition of these categories over time is the extent of the study area. Some studies include the entire delta, which comprises the northern part that was active prior to relocation of the river mouth from the Diaokou Promontory to the Qingshuigou Promontory in 1976, and the south-eastern Qingshuigou Promontory that is currently fluvially active (Figure 10), and that contains the Yellow River Delta National Nature Reserve, which is the focus area of this study (Figure 8).

Figure 10. Landsat images of the Yellow River Delta in 1979 and 2000, showing course change and change in delta area.

Xu and Liu (2003) examined the area of the entire Yellow River Delta using satellite images from 2 June 1976, 5 June 1986, and 20 September 1996. They found that while the area of the old delta (Diaokou Promontory) declined over the periods 1976–1986 and 1986–1996 through marine erosion, the current delta (Qingshuigou Promontory) area increased. The rate of increase in the current delta was 38 km²/yr in the period 1976–1986 and 11.7 km²/yr in the period 1986–1996. Xu and Liu (2003) used 1988 land resources survey data from Dongying District, Hekou District, Kenli County and Lijin County to measure the area of wetlands, and compared the results with measurements made from the 1996 satellite image. From 1988 to 1996, freshwater area increased according to the following categories: reservoirs 63.8 km², river 51.1 km², pond 63.1 km², and channel 14.1 km². Over the entire delta area, Xu and Liu (2003) measured an increase in reed area of 6.0 km² in 1996 compared to 1988, which they attributed to establishment of the Yellow River Delta National Nature Reserve in 1992.

Fan et al. (2006) reported literature that indicated that between 1972 and 1992 the delta area grew at the rate of 20–25 km²/yr. The value of 22.8 km²/yr average rate of growth for the period 1976–1992 given by Li and Chen (2003) is consistent with this range. Chu et al. (2006) used multi-temporal remote sensing data of Landsat MSS and TM from 1976–2000, totalling twenty scenes, to examine the changing pattern of accretion and erosion of the delta. Over this period, the total area of the Diaokou and Shenxiangou Promontories was reduced by 141.3 km², with a mean net erosion rate of 6.03 km²/yr. The total area of the Qingshuigou and Qing 8 Promontories increased by 384.16 and 11.88 km², respectively, with mean net growth rates of 16.4 and 3.03 km²/yr, respectively. In the period 1996 to 2000 Chu et al. (2006) measured a decline in delta area of about 66 km² (which is an erosion rate of about 16.5 km²/yr).

Chang et al. (2004) also measured the change in the area of the delta on the basis of analysis of 20 satellite images collected from 1976 to 2000 (Figure 11). The average rate of growth between 1977 and 1984 was 25.6 km²/year. This period was selected as the reference period for this study for comparing the rate of growth of the delta.
Figure 11. Change in area of the Qingshuigou and Qing 8 Promontories from 1977 to 2000, measured by Chang et al. (2004) from 20 satellite images.

Reference period
mean = 25.6 km²/yr

The selected reference period was from 1977 to 1984.

Zhang and Wang (2008) used Landsat MS and TM satellite data to measure the change in area of wetland vegetation categories in the Yellow River Delta over the period 1977–2004 (Figure 12). The maps in Zhang and Wang (2008) suggest that the entire delta was measured (i.e. including Diaokou, Shenxiangou and Qingshuigou Promontories), but the surface areas provided were much smaller than expected for an area of this size, especially the farmland area data. The data indicated that from 1987, the extent of Reed, Tamarisk, Suaeda and Farmland increased (Figure 12).

Figure 12. Change in area of main vegetation categories on the Yellow River Delta over time reported by Zhang and Wang (2008).

Note: *R. pseudoacacia* is *Robinia pseudoacacia* (black locust, a tree of the pea family Fabaceae, native to the United States).
4.4 Methodology

4.4.1 Remote sensing data analysis

Pre-processing of the remote sensing data included geometric correction and radiometric correction. The Landsat TM/ETM+ images were geo-referenced to a 1:50,000 topographic map using a nearest neighbour re-sampling algorithm with a root mean square error (RMSE) less than 0.5 pixels (15 m). On the condition that the weather data of the date image acquired was not available, dark pixel subtraction was applied to the images.

The satellite data was used to extract information on Reed, Tamarisk, Suaeda, farmland and coastline land cover categories using a combination of visual and automated interpretation.

The spectral characteristics of different surface features produce different pixel values. The different pixel values of each spectral band form spectral characteristics of different surface features that inform image interpretation. Due to different growing seasons of various plants, and varying crops being planted from season to season, crops and native vegetation can have similar spectral characteristics. Therefore, it was not possible to distinguish landscape types solely on the basis of spectral characteristics. However, areas of cultivation were easily discriminated due to the geometric boundaries and simple vegetation structure of such areas. Farmland has much more even texture than native vegetation. Farmland was first extracted by visual interpretation and then masked from the images.

Areas of known Reed, Tamarisk and Suaeda were identified on the images. Maximum likelihood classification was then applied to these selected areas. The initial results derived by computer algorithm were then improved with the aid of field survey data, texture information of the images, inter-relation of surface features, bio-geographical principles of where the communities should be found, and expert opinion.

The mean high-tide line was defined as the intersection of the plane of mean high water with the tidal flat. The mean high-tide line is a reasonable alternative to defining a coastline edge when tide level and topography data are unavailable. Tidal cycles create daily and seasonal fluctuations in the water content of tidal flats. Accordingly, the grey level, or colour, of the tidal flat varies in the remote sensing images. High elevation areas of the tidal flat tend to be light coloured, while the low-level tidal flat is darker. This colour difference aided image interpretation in the determination of mean high-tide line as a definition of the coastline edge.

4.4.2 Calculation of index scores

Most of the degradation of the delta wetlands is reported to have occurred after the 1980s (see Gippel et al. 2012a), so it was appropriate to set as reference the condition in the early-1980s. A suitable image was available for 1984, so the condition in that year was adopted as reference.

Vegetation composition comprised four vegetation types: Reed (r), Tamarisk (t), Suaeda (s) and Farmland (f). The composition (proportion of total delta (D) area) for each type was calculated for each year using Equation (1):

\[ C_i = \frac{A_i}{A_{D_t}} \]  

where
- \( C_i \) = composition of vegetation type \( i = r, t, s \) or \( f \) in year \( t \)
- \( A_i \) = observed area of vegetation type \( i = r, t, s \) or \( f \) in year \( t \)
- \( A_{D_t} \) = observed total area of delta (D) in year \( t \)

The index score \( I_{Ci} \) for Reed, Tamarisk and Suaeda was calculated for each year using Equations (2) or (3), which relate the relative area of each of the wetland vegetation types to their relative area in the reference year of 1984 \( C_i(1984) \):

\[ I_{C_r} = \frac{C_r}{C_{r(1984)}} , \quad \text{for} \quad C_r < C_{r(1984)} \]  

\[ I_{C_r} = 1 , \quad \text{for} \quad C_r \geq C_{r(1984)} \]  

Although Farmland reverts back to natural vegetation if abandoned, the overall area of Farmland has been monotonically increasing in the Yellow River delta. Farmland expansion was considered a threat to the value of wetland habitat, particularly for cranes. A score of 1 was assigned if the proportion of total delta area that was Farmland was equal to or less than the proportion in 1984. The highest tolerable proportion of Farmland was set at 1.5 times the reference proportion \( (C_{f(1984)} \), which was 19.3 per cent in 1984, giving a maximum tolerable 29.0 per cent of the delta area under Farmland. This value was based on expert opinion of the level beyond which the health of habitat
Assessment of river health in the Lower Yellow River

(partially for cranes) would be highly compromised, because humans would likely be proximal to a large percentage of the wetland area. The Farmland index was calculated using Equations (4), (5) and (6):

\[ I_{CF} = 1.5 \left( 1 - \frac{C_{ft}}{1.290} \right), \quad \text{for } 0.193 < C_{ft} < 0.290 \]  

(4)

\[ I_{CF} = 1, \quad \text{for } C_{ft} \leq 0.193 \]  

(5)

\[ I_{CF} = 0, \quad \text{for } C_{ft} \leq 0.290 \]  

(6)

The growth of the delta provides land for succession of vegetation, and habitats for birds and fish. The delta growth index \( I_D \) was calculated using Equations (7), (8) and (9), based on observed mean annual growth in area from the previous observation \( (R_{Dt}) \) (in km\(^2\)/year):

\[ I_D = \frac{R_{Dt}}{R_{(ref)}}, \quad R_{Dt} < R_{(ref)} \]  

(7)

\[ I_D = 1, \quad \text{for } R_{Dt} \geq R_{(ref)} \]  

(8)

\[ I_D = 0, \quad \text{for } R_{Dt} \geq A_{Dt0} \]  

(9)

where

\[ R_{Dt} = A_{Dt} - A_{Dt0} \]

\[ t = \text{year of observation} \]

\[ t0 = \text{year of previous observation} \]

\[ R_{(ref)} = \text{reference mean annual delta growth rate [for 1977 – 1984 = 25.6 km}^2/\text{yr (Chang et al. (2004)]} \]

The delta growth index score was not used in the delta vegetation health index score, but was used in the physical form group of indicators.

4.4.3 Aggregation of index scores

There are some important species of crane that use the Yellow River delta (i.e. *Grus grus*, *Grus japonensis*, *Grus vipio*, *Grus monacha* and *Grus leucogeranus*). For breeding, they tend to favour Reed habitat, together with Suaeda. Tamarisk is less suitable for crane species (see Gippel et al. 2012a). Red-crowned crane (*Grus japonensis*), an endangered species of high conservation significance in the delta, shows a strong preference for reed habitat. Wu and Zou (2011) reported that in the Zhalong Nature Reserve (Heilongjiang province) Reed swamps were selected by red-crowned crane in 93 per cent of cases.

Given that Reed habitat appears to be more important to cranes, the Reed category was given a higher weighting (0.6) than Tamarisk (0.2) and Suaeda (0.2). This is a simplistic relationship that does not take into account knowledge that red-crowned crane are particularly sensitive to human presence and human disturbance, and they also prefer habitats with water available. Also, as pointed out by Li et al. (2011), waterbird communities in restored wetlands of the delta were significantly different from those in natural and modified wetland components, and there was marked temporal variation in waterbird community composition in the various habitat types. Nevertheless, the simple model suggested here is a reasonable starting point for evaluating the relative availability of habitat preferred by cranes. Equation (10) was used to integrate sub indices of vegetation composition:

\[ I_c = 0.6 \ I_{Cr} + 0.2 \ I_{Cs} + 0.2 \ I_{Ct} \]  

(10)

where

\[ I_c = \text{integrated index score of vegetation composition} \]

\[ I_{Cr} = \text{sub-index score of Reed} \]

\[ I_{Cs} = \text{sub-index score of Tamarisk} \]

\[ I_{Ct} = \text{sub-index score of Suaeda.} \]

To provide a single index score of wetland vegetation condition, an overall score was calculated from the weighted scores of integrated vegetation composition and Farmland composition using Equation (11). The delta growth indicator was not included in this index because it was not directly related to vegetation, and because this index was better incorporated into the physical form indicator group. The wetland vegetation composition index was weighted higher than the Farmland composition index because it was more directly related to availability of desirable habitat:
\[ I_v = 0.8I_w + 0.2I_{cf} \]  \hspace{1cm} (11)

where

- \(I_v\) = integrated index score of delta vegetation health
- \(I_w\) = index score of wetland vegetation composition
- \(I_{cf}\) = index score of Farmland composition.

4.5 Data availability

4.5.1 Principles

Remotely sensed data can be obtained from many different satellites, with each providing data at particular resolutions and spectral bands. In general, the higher the resolution and the more spectral bands, the greater is the cost. As river health assessment is intended to be a routine and regular activity, cost is a major factor in determining the feasibility of any method. For assessment of vegetation in the delta, a number of requirements were established for remotely sensed data:

- data should be inexpensive, with archived data available
- the images should be acquired in summer or autumn, when vigorous vegetation provides a strong signal in the satellite image
- the images acquired in different years should be from the same season, or preferably the same month, of the year
- the images selected should be typical and representative of the period they represent.

4.5.2 Potential data sources

At present, satellites that offer free or archived data include Landsat TM/ETM+, SPOT5, IRS-P5, RADARSAT and CBERS.

SPOT-5 offers 10 m resolution (four multi-bands), improved 5 m and 2.5 m resolution (panchromatic band) and wide imaging swath, which covers 60 \(\times\) 60 km or 60 km \(\times\) 120 km in twin-instrument mode with temporal resolution of 26 days. The SPOT5 data, already available within YRCC for the delta, was acquired for December, 2007. Unfortunately, the winter season is not suitable for extracting information about wetland vegetation.

IRS-P5 is an Indian satellite, which carries two panchromatic cameras with 2.5 m resolution. Although it offers high-resolution data, the data scanned in panchromatic mode is not highly sensitive to vegetation.

Radarsat I and Radarsat II are two Canadian Synthetic Aperture Radar (SAR) satellites with a resolution capability ranging from 3 to 100 m. SAR is not particularly suited to identification of vegetation.

The first satellite of Landsat TM ([http://landsat.gsfc.nasa.gov](http://landsat.gsfc.nasa.gov)) was launched in 1983 with seven multi-spectral bands and swath of 185 km. The resolution of the data is 30 m with temporal resolution of 16 days.

The CBERS Program was developed from a partnership between Brazil and China in the space technical scientific segment. CBERS-1, launched in 1999, offers four bands of data with resolution of 19.5 m and swath of 113 km. This data can be freely acquired by the YRCC.

Based on the analysis of available data, Landsat TM/ETM+ and CBERS were most suited for the study. Although both CBERS and Landsat TM/ETM+ data can be acquired freely, Landsat TM/ETM+ data were chosen for the study due to longer historical series available, and more spectral bands being available. While it would have been possible to achieve better results in this study by purchasing and applying higher resolution data from alternative satellites, one of the main purposes of this study was to determine if a low-cost method could be established using free data.

4.5.3 Selected data

Considering the history of management of the delta and the data availability, Landsat TM/ETM+ images were acquired for four dates:

- 5 October 1984
- 23 September 1997
- 9 September 2002
- 2 October 2006.
4.6 Results

4.6.1 Satellite image analysis
The satellite image analysis method successfully distinguished patterns of change in land cover and delta surface area over the time period considered (Figure 13). After initially decreasing from 1984–1997, the area of Reed increased from 1997 to 2006 (Figure 14). However, the area of Tamarisk and Suaeda decreased from 1997–2002 and changed little from 2002–2006. The delta hydrological restoration program that began in 2002 (Source: modified from Li et al. (2011). Inserted (coloured) text taken from Li et al. (2011). Figure 8) was at least partly responsible for the increase in area of Reed observed over the past ten years (Figure 14).

4.6.2 Wetland vegetation assessment
The vegetation composition index scores indicated Reed composition increasing over time, Tamarisk composition decreasing, and Suaeda composition decreasing and then increasing (Table 9). This pattern gave an integrated vegetation composition score that suggested between 2002 and 2006, there was an improvement relative to the reference standards used here (i.e. more Reed and less Tamarisk) (Figure 15). The rate of conversion of land to Farmland decreased over time, especially since 2002, but the area of Farmland was always higher than reference, and increased in each period. The overall integrated delta vegetation health index score suggested that after a decline between 1997 and 2002, between 2002 and 2006 the vegetation pattern shifted closer to reference conditions and closer to a distribution that was associated with good wetland health. However, the scores were moderate, which reflects the vegetation health being considerably lower than it was in 1984.
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Figure 14. Change in area of main vegetation categories on the Yellow River Delta over time.


<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta growth (used in physical form indicator) ($I_{d}$)</td>
<td>1.00</td>
<td>0.29</td>
<td>0.00</td>
<td>0.15</td>
</tr>
<tr>
<td>Reed composition ($I_{r}$)</td>
<td>1.00</td>
<td>0.45</td>
<td>0.53</td>
<td>0.62</td>
</tr>
<tr>
<td>Tamarisk composition ($I_{t}$)</td>
<td>1.00</td>
<td>0.65</td>
<td>0.50</td>
<td>0.46</td>
</tr>
<tr>
<td>Suaeda composition ($I_{s}$)</td>
<td>1.00</td>
<td>1.00</td>
<td>0.60</td>
<td>0.61</td>
</tr>
<tr>
<td>Integrated vegetation composition score ($I_{v}$)</td>
<td>1.00</td>
<td>0.60</td>
<td>0.54</td>
<td>0.59</td>
</tr>
<tr>
<td>Farmland composition ($I_{f}$)</td>
<td>1.00</td>
<td>0.10</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Integrated delta vegetation health score ($I_{v}$)</td>
<td>1.00</td>
<td>0.50</td>
<td>0.43</td>
<td>0.47</td>
</tr>
</tbody>
</table>

The score was measured only for the indicated years.

Figure 15. Integrated (weighted) vegetation health score for the Yellow River Delta over time.
4.7 Discussion and Conclusion

In this study, Reed, Tamarisk, Suaeda, Farmland and coastline edge data were extracted for four historical dates from Landsat TM/ETM+ images. The data were used to calculate indices of wetland vegetation health, including vegetation composition, conversion of wetland to farmland, and delta area growth.

The results indicated that Landsat TM/ETM+ satellite data was suited to routine, cost-effective assessment of wetland vegetation health in the Yellow River delta, but at this stage the procedure is not fully automated. Further technical work might be able to increase the level of automation of the procedure, reducing subjectivity and processing time required.

The indicators developed here produced a result that was consistent with most of the scientific literature concerning the state of health of the delta over time. The results from 1997–2006 suggested a trend of declining and then improving health of the vegetation in the delta, with the improvement coming from an increase in the area of Reed (which can be explained by the artificial watering of part of the delta). It is of concern that the area of Farmland increased between 1984 and 2006, although the proportion of the delta area that was Farmland stabilised in 2006. While waterbird use of wetland vegetation in the Yellow River delta is complex, the simple indicators developed in this study may be adequate to monitor the overall direction of health in the delta.

The findings of this study contradict those of Zhang and Wang (2008), who also used Landsat imagery to measure the change in Reed, Tamarisk, Suaeda and Farmland over time on the Yellow River Delta. Zhang and Wang (2008) reported an overall increasing trend in the area of these vegetation types over the period 1977–2004, while this study found a general decrease over the period 1984–2006, except for Reed, which increased in area over the period 1997–2006. The reason for this difference is unclear.

Future work could consider development of methods for remote sensing of vegetation condition in riverine wetlands in reach 1 of the lower Yellow River (Xiaolangdi to Gaocun). These wetlands are smaller, and the vegetation patches potentially smaller and more complex. This will likely require higher resolution satellite data.
Chapter 5. Hydrology

The hydrology component of the river health assessment for the lower Yellow River was undertaken by a team from Yellow River Conservancy Commission, Zhengzhou. The work was documented in three ACEDP technical reports:

- Gippel et al. (2012a) provided a comprehensive statistical characterisation of the available hydrology data from the lower Yellow River for the purpose of informing the environmental flows assessment process.
- Gippel et al. (2012b) used the hydrological characterisation of Gippel et al. (2011a) to formulate environmental flow recommendations for the lower Yellow River. The historical flow regime was then checked for compliance with the recommended regime using a method known as Index of Flow Health (IFH).
- Gippel et al. (2011a) evaluated a number of existing methods, and developed two new methods, of assessing hydrological alteration for the purpose of river health assessment. The two new methods were known as the Index of Flow Deviation (IFD) and the IFH. The lower Yellow River was one of the case studies used in demonstrating application of the various methods that were trialed.

This section of the report comprises edited extracts from Gippel et al. (2012a, 2012b, 2011a). More details can be found in the original reports.

5.1 Rationale for inclusion

Hydrology is an important controlling variable of the health of biota in streams, so it is often included in river health assessment programs. Hydrology can be assessed for the purpose of providing contextual information that aids interpretation of ecological data, or it can be included as a component of a multi-metric river health index. In regulated rivers, the hydrology is at least partly manageable, so in this situation, one potential benefit of a hydrological assessment is identification of aspects of hydrological management that can be altered for the benefit of the ecology.

Assessments of hydrologic alteration are often based around the natural flow paradigm (Lytle and Poff 2004), which emphasises evolutionary links between patterns of flow variability (timing, frequency and magnitude of different flows) and morphological, behavioural and life-history adaptations of the biota. Increasing levels of flow alteration are expected to increase the risk that such evolutionary linkages will be disrupted (Bunn and Arthington 2002). While there is much complexity, and by no means perfect links, between hydrologic alteration and ecological change, measures of hydrologic alteration provide a simple means of assessing potential risk. There is also a need to better understand the links between flow regime characteristics and ecological patterns and processes in particular regions to help inform this risk assessment process.

Hydrology indicator values might be used as part of a multi-metric index (as in this lower Yellow River pilot study), or they might be used to inform the narrative associated with the report card (as in the Pearl and Liao pilot studies). They also allow river managers to check the compliance of the flow regime against any environmental flow requirements that apply to the river.

5.2 Background to methodology

Gippel et al. (2011a) developed and trialled methods suitable for characterising the hydrology of the Taizi (Liao River Basin), Gui (Pearl River Basin) and Lower Yellow (Yellow River Basin) rivers in a way that has direct meaning for ecological health. Four contrasting approaches to hydrological characterisation were taken:

1. application of an existing rapid method of characterising hydrological alteration, with the method adopted here being the Flow Stress Ranking (FSR) procedure
2. application of the Chinese Hydrology and Water Resources Index (HD), which has been proposed for a nation-wide river health assessment program
3. development of the IFD, a suite of flow deviation indicators based on historical monthly flows
4. development of the IFH, that used environmental flows compliance testing as a river health index.

For a test year, or test period, the FSR, HD and IFD attempt to answer the question:

- “Do general hydrological parameters, thought to be either universally important or universally undesirable for maintaining good river health, have characteristics that are different to those of the reference (natural or unimpaired) flow regime?”
The IFH offers a fundamentally different way of assessing hydrology compared to that followed by the FSR, HD and IFD. For a test year, or test period, the IFH attempts to answer the question:

- ‘To what degree do specific hydrological parameters, identified as either locally important or locally undesirable for maintaining river health to an agreed standard, occur in the current flow regime?’

Gippel (2011a) applied the FSR, HD and IFD methods to the Taizi, Gui and lower Yellow Rivers, while the IFH was applied only in the Taizi River. The IFH requires that an environmental flow assessment has been undertaken, so when an assessment was completed for the lower Yellow River, the IFH was calculated (Gippel, 2012b).

The overall findings of the testing of the four methods of hydrological characterisation were:

- FSR indicators are relatively easy to calculate from monthly flows, and they show sensitivity to hydrological alteration. However, the results can be difficult to interpret in terms of river health impacts, and do not necessarily assist in deciding the most appropriate course of management action.

- The HD index proposed for China’s nation-wide river health assessment program suffers some limitations in terms of where it can be applied. Also, concerns were raised about application of the simple Tennant method of relating hydrological factoring to ecosystem health.

- The IFD was designed to work with monthly historical flow data. It comprises eight indicators, with each one having conceptual relevance to ecosystem health. The IFD, with its focus on highlighting deviations of flow parameters beyond a reasonable range of natural variability, proved to be adequate as a river health index. The IFD highlights impacts of flow regulation, and also highlights years of naturally lower than usual flows, both of which are important determinants of ambient ecological health, as measured using bioassessment methods. At the very least, the IFD provides a simple way of establishing the relative hydrological health of rivers at the national and regional scales for gauging stations that have pre-regulation flow data available.

- Given that the IFD is a hydrology-only approach, and the monthly time-step is relatively coarse from the perspective of ecological processes, the connection between the index scores and ecological health is only at the conceptual level. The IFH was developed to assess the degree of compliance of environmental flow components with the standards expected for an agreed level of ecological stream health. The IFH is effective because it communicates to river managers those aspects of the flow regime needing attention to improve river health.

- Application of IFH will be limited mostly to large river mainstems, and rivers that are highly valued for their ecological or economic values. The IFD index scores were correlated with the IFH index scores, suggesting that the IFD could be a reasonable indicator for use in rivers where an environmental flow assessment has not been undertaken.

For the Yellow River, the preferred indicators are the IFD and the IFH. The IFD would find application in a basin-wide comparison of flow health, while the IFH is the superior method for the lower Yellow River, where an environmental flow assessment has been completed. This report does not provide any details of the IFD or IFH methodologies; readers seeking this information should refer to Gippel (2012b) and Gippel (2012c).

5.3 Objectives

Development of the IFD and IFH methodologies involved calculation of the indicators for each year of fairly long time series (from the 1950s to the present). This was done to demonstrate that the indicators were sensitive to the normal range of hydrological variability, and to compare the hydrological change over time with the pattern of water resources development and anecdotal reports of trends in river health. For routine river health reporting, there is no need to document the long-term historical time series of hydrological health, but the hydrology of previous 3–10 years might be relevant to the ecological conditions of the current year. So, while a report card might illustrate the IFD or IFH scores for the current or past year, it might also include a graph of the trend in the scores over the previous 3–10 years.

This report compiles the IFD and IFH results for the lower Yellow River from Gippel (2011a) and Gippel (2012b) respectively, with a focus on reporting data suitable for integration into a river health report card.
5.4 Index of Flow Deviation (IFD)

5.4.1 Basic concepts of the IFD

The IFD was designed to work with monthly historical flow data. It comprises eight indicators, with each one having conceptual relevance to ecosystem health. The eight indicators comprise:

- HFV (high-flow volume)
- HMF (highest monthly flow)
- LFV (low-flow volume)
- LMF (lowest monthly flow)
- PHF (persistently higher flow)
- PLF (persistently lower flow)
- PVL (persistently very low)
- SFS (seasonality flow shift).

As a basic standard for any hydrological parameter, the IFD adopted the inter-quartile range (25th to 75th per centile) within the natural flow series as the range within which the hydrological health score would be 1 (over the range 0–1). Deviations in a parameter beyond that range potentially score less than 1 (depending on how deviations are scored), which accepts that in a reference flow series, on average, up to 50 per cent of the time the score will be less than 1.

The eight IFD indicators characterise the main forms of ecologically relevant hydrological deviation from reference, whether these be due to natural variation or regulation (Figure 16). Five of the eight IFD indicators (i.e. HFV, LFV, HMF, LMF and SFS) are sensitive to the natural inter-annual variance of the indicator in the reference series. If these indicators are highly variable in the reference series, then high deviations in a test year would not attract a high deviation score. On the other hand, in a river that naturally has low inter-annual variance, increased inter-annual variability of the indicators in the regulated regime will attract a high deviation score. Flow persistence (measured by indicators PLF, PHF and PVL) did not occur most of the time in the reference series, and when it occurred, it lasted for only a few months. The distributions of persistence (characterised by few values over a limited range) were not suitable as a reference from which to calculate a deviation score. So, the persistence indicators were scored against a standard that covered the possible range of the indicator values.

Figure 16. Illustration of the eight aspects of flow regime deviation characterised by the IFD indicators.

Note: These data are not from the lower Yellow River.
5.4.2 IFD results

The IFD indicators were derived for each year in the available historical monthly flow time series for the four Lower Yellow River gauging stations Huayuankou (1950–2008); Sunkou (1953–2008); Luokou (1950–2008); and Lijin (1951–2008). The reference statistics for the indicators were derived from modelled reference data for Huayuankou and Lijin, and from historical data prior to regulation by dams for Sunkou and Luokou, because modelled reference data was not available for these two gauges.

The annual IFD index score calculated over the time series for the four Lower Yellow River stations indicated a degree of inter-annual variability, which reflected natural variability in hydrological conditions (Figure 17). The scores showed a general decline over time since Sanmenxia began operation in late 1960 (Figure 17). From the beginning of the record up to 1995 the IFD index scores varied cyclically, possibly in connection with natural climatic variation. All four stations showed a small but persistent rise in IFD score after the operation of the Xiaolangdi Dam began in October 1999 (i.e. water year 2000), particularly since water sediment discharge regulation (WSDR) began in 2002 (Figure 17).

The advantage of the overall IFD index score is its simplicity for presentation, but this is also a weakness, because the detail of how individual characteristics of the flow regime have changed is lost. The full suite of IFD indicators can be presented in a relatively simple way by placing the scores within five flow deviation classes (Figure 18).

For regular river health card reporting, the full historical time series is of less interest than detail concerning the most recent period, with the previous three years probably being the most relevant to the ecological conditions of the current year (Figure 19).

Figure 17. Time series of IFD index scores for four Lower Yellow River system stations.
Figure 18. Time series of IFD indicator scores in five classes of deviation for four Lower Yellow River system stations.

Note: Coloured text for years indicates regulation phases
Figure 19. Detailed IFD indicator scores for Lower Yellow River systems stations for the last three years of available record.

Note: Each indicator scored on the scale 0–1.
5.5 Index of Flow Health

5.5.1 Basic concepts of the Index of Flow Health

It is easy to calculate the degree of flow deviation for selected hydrological indicators (such as the IFD). However, this is very different from the process of determining the degree to which various critical aspects of the flow regime can be altered, yet retain or reinstate the desired level of river health. One of the problems is that flow alone says nothing about hydraulic factors that are very important to the biota, namely water depth, velocity, wetted perimeter, and shear stress. Flow data alone can easily characterise the cease to flow condition of a channel, but definition of all other aspects of hydraulic habitat availability needs more information. For example, floodplains (and their associated riparian and wetland environments) are inundated only when the river breaks its banks (or a sill to a low-lying floodplain feature such as a wetland or anabranch), so characterisation of the floodplain connection and disconnection is a function of the relationship between the elevation of the floodplain and the elevation of the river flow (i.e. the hydraulics), not just river flow.

In a holistic assessment of environmental flow needs, it is normal practice to consider, and model, the hydraulic factors that are important to the biota. The environmental flow regime is then based on the hydraulic, hydrologic, and other flow-related environmental needs of the locally identified key environmental assets. This process was followed for the lower Yellow River (Gippel et al. 2012a; Gippel et al. 2012b). The YRCC was interested to develop more than one set of environmental flow options, to assist decision making in the face of intense competition for water resources. For the lower Yellow River, two flow options were developed, one for low risk to ecological river health, and one for medium risk to ecological river health (Gippel et al. 2012b).

Most conceptual models exploring the influences of flow variation on river ecosystems identify key flow components (characteristics of the flow regime) that serve important physical and biological functions. Environmental flow components have hydrological characteristics that require specification in order that they can be implemented into a practical flow regime (Table 10). The specifications are made with an (explicit or implicit) understanding that they would have a high probability of achieving their intended ecological objectives, and a low risk of bringing about unexpected or undesirable ecological outcomes. Therefore, certainty of achieving a high level of river health would likely require a suite of flow components specified with a high cost in water, while the suite of components required to achieve a modest level of river health would likely cost less water. 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.

Table 10. Flow components that comprise the flow regime.

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

Gippel et al. (2011a) developed the IFH as a way 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, designed to achieve the agreed level of river health. Compliance, as used here, is not a test of how well the managing authority historically
conformed with a licence, regulation or guideline. Rather, it is a test of how well the historical flows would have conformed with the flow recommendations made here. The main purposes of compliance analysis are: (i) to provide river managers with an idea of the extent to which they would need to alter their historical practices if they were to meet the flow recommendations made here, and (ii) to provide river managers with an indication of how often natural hydrological conditions such as drought might prevent meeting the flow recommendations made here.

As the environmental flow event objectives are specified in multi-dimensional terms of magnitude, duration, annual frequency and inter-annual frequency, the IFH uses a sophisticated form of spells analysis to determine the compliance of each of the flow components. The event-based environmental flow components (pulses and bankfull) are specified with a requirement for a minimum inter-annual frequency. The IFH score takes account of this by measuring the occurrence of the event in the year in question, plus in the number of previous years that sum to the period over which the inter-annual frequency was specified. In the case of the Lower Yellow River, the inter-annual frequency was specified for a five-year period. So, the event-component scores for each year contain a ‘memory’ of the occurrence of the events in the previous four years.

5.5.2 Weighting Index of Flow Health component scores

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. 2012b). 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. Therefore, an integrated IFH index score \((IFH_1)\) was derived by weighting the individual IFH indicator scores according to the following relationship:

\[
IFH_1 = a_1 CTF + a_2 LF + a_3 HF + a_4 \left(\frac{LFR + LFF}{2}\right) LFP + a_5 \left(\frac{HFR + HFF}{2}\right) HFP + a_6 \left(\frac{HFR + HFF}{2}\right) BF
\]

where

- \(a_1, a_2, a_3, a_4, a_5, a_6\) = weighting coefficients specific to each IFH flow component (Table 11)
- \(CTF = \text{cease to flow score}\)
- \(LFR = \text{low-flow rate of rise score}\)
- \(LFF = \text{low-flow rate of fall score}\)
- \(LF = \text{low-flow score}\)
- \(LFP = \text{low-flow pulse score}\)
- \(HFR = \text{high-flow rate of rise score}\)
- \(HFF = \text{high-flow rate of fall score}\)
- \(HF = \text{high-flow score}\)
- \(BF = \text{bankfull flow score}\)
Table 11. Weighting coefficients used to calculate integrated IFH score for the lower Yellow River.

<table>
<thead>
<tr>
<th>Reach (e-flow option)</th>
<th>Cease to flow</th>
<th>Low flow</th>
<th>Low-flow pulse</th>
<th>High flow</th>
<th>High-flow pulse</th>
<th>Bankfull</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CTF</td>
<td>LF</td>
<td>LFP</td>
<td>HF</td>
<td>HFP</td>
<td>BF</td>
</tr>
<tr>
<td></td>
<td>$a_1$</td>
<td>$a_2$</td>
<td>$a_3$</td>
<td>$a_4$</td>
<td>$a_5$</td>
<td>$a_6$</td>
</tr>
<tr>
<td>1 (low-risk)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>1 (med-risk)</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2 (low-and med-risk)</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>3 (low-and med-risk)</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>4 (low-and med-risk)</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

5.5.3 Results of Index of Flow Health

The annual compliance time series for the lower Yellow River was 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 presented in this report, the main dam regulation phases are indicated using coloured text for the date scale:

- grey text = pre-Sanmenxia Dam (SMX)
- blue text = post-SMX and pre-Liujiaxia Dam (LJX)
- orange text = post-LJX Dam and pre-Longyangxia Dam (LYX)
- green text = pre-Xiaolangdi Dam (XLD) and post-LYX Dam
- red text = post-XLD.

Compliance was measured as an index score over the range 0–1. The score was then placed within a five-class scale, ranging from very good (perfect or close to perfect compliance) to critical (flows diverge greatly from the recommended environmental flows).

The compliance check of low and high-flow components (i.e. baseflows) by month indicated that non-compliance did not occur until 1958 (Figure 20, Figure 21, Figure 22 and Figure 23). The compliance plots reflect the historical patterns in water resource availability and use in the lower Yellow River (see Gippel et al. 2012a; Gippel et al. 2012b). Anecdotal information (see Gippel et al. 2012a) 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 low and high-flow component scores.
Reach 1

Figure 20. Time-series of monthly high-flow and low-flow compliance at Huayuankou (reach 1) for low-risk (top) and medium-risk (bottom) environmental flow regime.

Reach 2

Figure 21. Time-series of monthly high-flow and low-flow compliance at Sunkou (reach 2) for low-risk (top) and medium-risk (bottom) environmental flow regime.
Reach 3

Figure 22. Time-series of monthly high-flow and low-flow compliance at Luokou (reach 3) for low-risk (top) and medium-risk (bottom) environmental flow regime.

Reach 4

Figure 23. Time-series of monthly high-flow and low-flow compliance at Lijin (reach 4) for low-risk (top) and medium-risk (bottom) environmental flow regime.
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 (12). 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 24, Figure 25, Figure 26 and Figure 27).

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 before 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 therefore low compliance) because the channel had incised significantly since the WSDR began in 2002, so higher magnitude flows are now required to reach the same elevation as previously. Before incision of the channel, this flow component would have been satisfied by a lower discharge threshold so, in reality, before 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 Longyangxia Dam started operating in 1969. 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 3000 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 the 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 3000 m$^3$/s in the first few years of operation of the dam.

Reach 1

Figure 24. Time-series of annual compliance for all flow components at Huayuankou (reach 1) for low-risk (top) and medium-risk (bottom) environmental flow regime.
Reach 2

Figure 25. Time-series of annual compliance for all flow components at Sunkou (reach 2) for low-risk (top) and medium-risk (bottom) environmental flow regime.

Reach 3

Figure 26. Time-series of annual compliance for all flow components at Luokou (reach 3) for low-risk (top) and medium-risk (bottom) environmental flow regime.
Reach 4

Figure 27. Time-series of annual compliance for all flow components at Lijin (reach 4) for low-risk (top) and medium-risk (bottom) environmental flow regime.

Cease to flow had poor compliance in reaches 3 and 4 after the Longyangxia Dam started operating, but compliance was very good after the Xiaolangdi Dam started operating 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 the Longyangxia Dam began operating. Construction of dams provided the control over flow that allowed irrigation to flourish in the lower Yellow River area. Therefore, 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.

5.6 Results

Both IFD and IFH are suitable for inclusion in a multi-metric river health index. In the case of the lower Yellow River, the IFH was preferred, because it reflects local flow needs determined through an environmental flow assessment procedure. While the medium-risk environmental flow option might be useful for assisting management decisions, the low-risk environmental flow option was preferred as the reference for river health.

The overall weighted IFH score time series from the 1950s to 2008 shows that apart from low scores in 1960 associated with an overly ambitious start to expansion of irrigation, scores began to decline in the 1970s, but deteriorated markedly in the 1990s (Figure 28). The late 1990s are well-recognised as the worst period for river flow and river health in the lower Yellow River, especially in 1997, when cease to flow conditions prevailed for long periods in the lower part of the river. With the operation of the Xiaolangdi Dam, the IFH index scores showed a dramatic improvement for the three lower reaches (reach 1 was not previously impacted by cease to flow) (Figure 28). In 2004 the baseflows were increased, and this lead to a further increase of the IFH integrated score (Figure 28).
Figure 28. Time-series of annual compliance for all flow components at Lijin (reach 4) for low-risk (top) and medium-risk (bottom) environmental flow regime.

The IFH scores for 2008 (Figure 29) indicate high compliance with cease to flow, high flow and low flow, except at reach 4. The low-flow pulse required at reach 1 was absent, and the bankfull component was poor or worse at reaches 2, 3 and 4.

Figure 29. Index of Flow Health scores for the four reaches of the lower Yellow River for 2008.

Note: Rate of rise and fall scores not shown.
Chapter 6. Water Quality

The water quality component of the river health assessment for the lower Yellow River was undertaken by a team from Yellow River Conservancy Commission, Zhengzhou. Some of the work was documented in Gippel et al. (2012a), which provided a statistical characterisation of the water quality data from the lower Yellow River for the purpose of informing the environmental flows assessment process. This section of the report comprises edited extracts from Gippel et al. (2012a). More detailed information can be found in the original report.

6.1 Rationale for inclusion

Water quality is a key component of aquatic ecosystem condition. Measures of the physical and chemical condition of the water column are often included in ecosystem health monitoring and assessment programs. Chemical components may also act as stressors on aquatic biota. Water quality is already widely monitored in China according to a national standard, mainly at mainstream sites. Therefore, in addition to including specific water quality measurements in new initiatives to assess river health, existing datasets can be evaluated and the data from these programs incorporated into the new initiatives.

The key aspects of water quality measured included the basic physico-chemical properties of the water (temperature, pH), nutrient concentrations, metallic and non-metallic toxicants and oxygen balance parameters. The Chinese standard does not include electrical conductivity (EC), turbidity, or total suspended solids (TSS), but these parameters are sometimes measured. For example, TSS is measured regularly on the lower Yellow River. These parameters are typically included in river health surveys. They relate to a range of potential sources, including agricultural, domestic and industrial point-source pollution, as well as diffuse inputs associated with runoff from the broader catchment. The relative concentrations of nutrients and pollutants can generally provide an indication of the likely sources in the upstream catchment or local area. These data help to identify critical areas to be addressed by management actions. Degraded water quality is often regarded as the main threat to river health in Chinese rivers. The Chinese government has for some time regarded this as a priority area for river management. Inclusion of water quality parameters in a river health assessment program will allow assessment of the success, or otherwise, of these initiatives.

One of the advantages of including water quality parameters as a suite of indicators is that there are often independently prescribed standards for different uses (e.g. drinking water, human contact, and tolerances of biota), eliminating or reducing the need to determine reference condition targets as an exercise within the river health program. There may be cases of healthy rivers where some aspects of water quality reach values that elsewhere could be associated with ecological degradation. This relates to site or regional variations in the tolerances of aquatic biota to the chemical and physical properties of river water. However, the existence of water quality data for so many systems around the world means that the range of values that different water quality parameters might take, for example, in tropical versus desert streams, is relatively well documented (e.g. Wetzel 2001).

A critical problem with monitoring water quality is that most parameters vary over a very large range according to the pattern of hydrology. For example, immediately following a dry period the flushing of material from streambanks, drains and other areas can temporarily elevate contaminant concentrations to high levels. The concentration of contaminants is also influenced by the degree of dilution, so if the input rate of contaminants is relatively stable, their concentrations can be low under high-flow conditions, and high under low-flow conditions.

Bioassessment programs usually take spot measurements of water quality at the same time that fish, algae or macroinvertebrates are sampled. If the stream under investigation is regularly sampled as part of an established water quality monitoring program, then it is preferable to use those data rather than spot data. Comparing spot data with the regularly sampled data might be useful to determine if there was an unusual pollution event affecting the site at the time of biological sampling.

A number of sites along the lower Yellow River are included in an established water quality monitoring program. Therefore, there was no need to undertake separate sampling for the water quality component of the river health assessment.
6.2 Background to methodology

Gippel et al. (2012a) reviewed all readily available water quality data and published analyses of water quality data from the lower Yellow River. This review found that water quality was degraded in some respects that would pose a threat to the ecological health of the river. A standard method was devised for analysing and presenting monthly water quality data. The objectives of that work did not include seeking obsolete or highly correlated parameters to reduce the indicator set to a minimum number of parameters. This was not necessary because the data are collected independently and, therefore, impose no additional cost to the river health assessment program. The approach taken here was to include in the analysis as many of the available parameters as possible.

6.2.1 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 12). 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. 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 percentage of its length that falls within each grade. Each sampling point is assumed to represent a certain length of river.

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 13).

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 14).

<table>
<thead>
<tr>
<th>Grade of water use</th>
<th>Description of water use</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>National nature conservation reserves; water source protection zones</td>
</tr>
<tr>
<td>II</td>
<td>Drinking water 1st Class; natural habitat for sensitive and rare aquatic species; fish and crustacean spawning; fish rearing</td>
</tr>
<tr>
<td>III</td>
<td>Drinking water 2nd Class (treatment required); sanctuaries for common aquatic species; fish survival in winter; fish migration; aquaculture; contact recreation</td>
</tr>
<tr>
<td>IV</td>
<td>Industrial use; active non-contact recreation</td>
</tr>
<tr>
<td>V</td>
<td>Industrial cooling only; agricultural irrigation; ordinary (low conservation value) landscape irrigation; passive recreation</td>
</tr>
<tr>
<td>VI</td>
<td>Not suitable for any purpose</td>
</tr>
</tbody>
</table>
Table 13. Chinese water quality grades, arranged by classes of use, and an arbitrary aquatic health rating.

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

S means suitable for use, and U means unsuitable for use.
Table 14. The 24 water quality parameters listed in GB3838-2002, arranged by three major categories and five sub-categories for chemical parameters.

<table>
<thead>
<tr>
<th>Parameter category</th>
<th>Symbol</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic parameter</td>
<td>°C</td>
<td>Water temperature</td>
</tr>
<tr>
<td>Chemical parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic parameter</td>
<td>pH</td>
<td>Relative acidity</td>
</tr>
<tr>
<td>Metallic toxicants</td>
<td>Cu</td>
<td>Copper</td>
</tr>
<tr>
<td></td>
<td>Zn</td>
<td>Zinc</td>
</tr>
<tr>
<td></td>
<td>Se</td>
<td>Selenium</td>
</tr>
<tr>
<td></td>
<td>As</td>
<td>Arsenic</td>
</tr>
<tr>
<td></td>
<td>Hg</td>
<td>Mercury</td>
</tr>
<tr>
<td></td>
<td>Cd</td>
<td>Cadmium</td>
</tr>
<tr>
<td></td>
<td>Cr$_{6+}$</td>
<td>Hexavalent chromium</td>
</tr>
<tr>
<td></td>
<td>Pb</td>
<td>Lead</td>
</tr>
<tr>
<td>Non-metallic toxicants</td>
<td>F-</td>
<td>Fluoride</td>
</tr>
<tr>
<td></td>
<td>CN-</td>
<td>Cyanide</td>
</tr>
<tr>
<td></td>
<td>P*</td>
<td>Volatile phenols</td>
</tr>
<tr>
<td></td>
<td>LAS</td>
<td>Anionic surfactant</td>
</tr>
<tr>
<td></td>
<td>H$_2$S (DS)</td>
<td>Sulphide</td>
</tr>
<tr>
<td></td>
<td>CH$_4$</td>
<td>Petroleum hydrocarbons</td>
</tr>
<tr>
<td>Nutrients</td>
<td>TN</td>
<td>Total Nitrogen</td>
</tr>
<tr>
<td></td>
<td>TP</td>
<td>Total phosphorus</td>
</tr>
<tr>
<td></td>
<td>NH$_3$-N</td>
<td>Ammonia Nitrogen</td>
</tr>
<tr>
<td>Oxygen balance parameters</td>
<td>DO</td>
<td>Dissolved oxygen</td>
</tr>
<tr>
<td></td>
<td>COD</td>
<td>Chemical oxygen demand</td>
</tr>
<tr>
<td></td>
<td>COD$_{mn}$</td>
<td>Permanganate Index</td>
</tr>
<tr>
<td></td>
<td>BOD$_5$</td>
<td>5-day biochemical oxygen demand</td>
</tr>
<tr>
<td>Bacterial parameters</td>
<td>Faecal coliform</td>
<td>Faecal coliform</td>
</tr>
</tbody>
</table>
6.2.2 Data availability

The water quality of each of the four river health assessment reaches was characterised on the basis of monthly data over the period 1994–2009 from a monitoring station located within the reach (Figure 5). The data was provided by YRCC. The records had occasional gaps in monthly data for various parameters, but there was sufficient data for each year to calculate an annual value of water quality grade.

Not all 24 parameters listed on GB 3838-2002 are measured at lower Yellow River stations (Figure 30). For example:

- anionic surfactant and selenium have never been measured
- sulphide has only been measured on a few occasions
- total nitrogen (TN) was only monitored in 2002, 2003 and 2004 at Gaocun, Luokou and Lijin and in 1994-1998 at Huayuankou
- total phosphorous (TP) and faecal coliform were included in the monitoring program at Gaocun, Luokou and Lijin around the time of introduction of the new standard in 2002
- TP was monitored at Huayuankou before the 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 Luokou station (Figure 30).

6.2.3 Method of assigning an annual score for meeting water quality grade

The official target water quality grade for the lower Yellow River is Grade III. This grade is appropriate for industrial and agricultural use of river water (for use in a social river health index), but it is inappropriate as a standard for aquatic health. A high compliance with achievement of Grade II would likely be associated with medium to high aquatic health, if no other factor was limiting to river health (Table 13). Therefore, for this river health assessment, Grade II was adopted as the standard. There is scope to improve on the water quality standards required for aquatic health in the lower Yellow River, and more generally in the whole of China.

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. 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 a 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 phosphorus is associated with particulate matter such as silt and clay sourced from the Loess Plateau. The TP limits in GB 3838-2002, which are similar to those for Australian rivers, 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 the 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 five-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 30). 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 30). For the purpose of examining the pattern of overall water quality from 1994–2009, 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 et al. 2010).
Figure 30. Availability of monthly water quality data for lower Yellow river stations from 1994–2002 for parameters listed on GB 3838-2002.

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 (as for all other analyses in this river health assessment).
4. Set the seasons
In the lower Yellow River, splitting the year into two six-month periods based on hydrological characteristics gave the high-flow season as June–November and low-flow season as December–May, as for all other analyses in this river health assessment.

5. Determine the grade score for each month in the record, assessed over all included parameters
6. For each year, count the number of months that met the target grade (or better).
7. 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.

The indicators were denoted as:

\[ WQ_A = \frac{M_A}{12} \]  
\[ WQ_H = \frac{M_H}{6} \]  
\[ WQ_L = \frac{M_L}{6} \]

where

- \( WQ_A \) = number of months (as a proportion of the year) that the target grade (or better) was met over a year (\( M_A \))
- \( WQ_H \) = number of months (as a proportion of the season) that the target grade (or better) was met over the high-flow period (\( M_H \))
- \( WQ_L \) = number of months (as a proportion of the season) that the target grade (or better) was met over the low-flow period (\( M_L \)).

6.2.4 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 dissolved oxygen) would result in a step-wise improvement to the next grade.

A score was assigned for limiting parameters for the six water quality parameter categories (Table 14). Temperature was not included as a category because a standard was unavailable. The proportion of months of the year that any of the parameters within the parameter categories limited the water quality grade was calculated (i.e. prevented the monthly sample from being assigned to a higher grade). An index was then derived according to Equations (16) to (21):

\[ WQ_{OX} = 1 - P_{OX} \]  
\[ WQ_N = 1 - P_N \]  
\[ WQ_M = 1 - P_M \]  
\[ WQ_{nM} = 1 - P_{nM} \]  
\[ WQ_{pH} = 1 - P_{pH} \]  
\[ WQ_{FC} = 1 - P_{FC} \]

where

- \( WQ_{XX} \) = an annual index in the range 0–1 that indicates how often parameter values from the parameter group \( XX \) was limiting water quality grade (zero means always limiting, 1 means never limiting)
- \( P_{XX} \) = the proportion of months of the year that any of the parameters within the parameter category \( XX \) limited achievement of a higher water quality grade
- \( OX \) = subscript denoting oxygen balance parameter category
- \( N \) = subscript denoting nutrient (ammonia nitrogen) parameter category (TN and TP excluded)
- \( M \) = subscript denoting metallic toxicant parameter category
- \( nM \) = subscript denoting non-metallic parameter category
- \( pH \) = subscript denoting relative acidity (pH) parameter category
- \( FC \) = subscript denoting bacterial (faecal coliform) parameter category (not used in aquatic health assessment).
6.3 Results

6.3.1 Trend in annual and seasonal scores

The management target Grade III was achieved 30–80 per cent of the time prior to 1999 (Figure 31). 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 31).

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 32). 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 32). These data strongly suggest that water quality is limiting ecological river health.

6.3.2 Index values for 2008

The annual scores, $WQA$, for aquatic health for 2008 indicate poor to critical water quality (Figure 33). The data indicate that most of the time Grade II was not met. The index scores for the parameter categories that limited achievement of a higher water quality grade indicated that the oxygen balance and nutrient categories were limiting, while pH, metallic toxicants and non-metallic toxicants rarely limited the grade (Figure 33).

The annual scores, $WQH$, for human uses for 2008 indicate good or very good water quality (Figure 34). The data indicate that most of the time, Grade III was met. The index scores for the parameter categories that limited achievement of a higher water quality grade indicated that the oxygen balance, bacteria (faecal coliform) and nutrient categories were limiting, while pH, metallic toxicants and non-metallic toxicants rarely limited the grade (Figure 34).

6.4 Discussion

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 its 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 the 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 the Xiaolangdi Dam has been a factor in the observed improvements in water quality since 2000.

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).

The target water quality for the lower Yellow River (Grade III) is currently met most of the time, with a marked progressive improvement apparent after 2000. The improvement is likely partly due to pollution control programs, partly due to trapping of fine sediment (with contaminants attached) in Xiaolangdi Dam, and partly due to dilution and assimilation of contaminants through the release of baseflow water from Xiaolangdi Dam.

Although there has been a massive improvement in water quality in the lower Yellow River since the late 1990s, the standard currently achieved is probably still too low to allow a high level of river health.
Figure 31. Time series of per cent of time that water quality Grade III was achieved (, and ) on the lower Yellow River from 1994–2009.

Annual

High flow season

Low flow season
Figure 32. Time series of per cent of time that water quality Grade II was achieved (, and ) on the lower Yellow River from 1994–2009.
Figure 33. Water quality (aquatic health) scores for the four reaches of the lower Yellow River for 2008.

Annual score is the index value. Scores for parameter categories indicate the frequency that parameters from that category limited achievement of a higher water quality grade.

Figure 34. Water quality (human use) scores for the four reaches of the lower Yellow River for 2008.

Annual score is the index value. Scores for parameter categories indicate the frequency that parameters from that category limited achievement of a higher water quality grade.
Chapter 7. Physical Form

7.1 Rationale for inclusion

Physical form is included in many modern river health assessment programs (Gippel 2011b), for example, the EU Water Framework Directive (Kallis 2001), and the Australian Framework for the Assessment of River and Wetland Health (FARWH) (Norris et al. 2007). In this context, physical form encompasses fluvial geomorphological process and form, or the interaction of sediment, flowing water, and organic factors (growing and dead vegetation) to shape river channels and floodplains. Physical form is included because, together with chemical processes (water quality), radiation (energy from the sun), and hydrological processes (river flow regime), geomorphological processes provide the template upon which ecological processes proceed.

Geomorphological condition is defined as the balance of sediment supply, transport capacity and resistance to erosion, which gives rise to a distribution of physical forms at a range of scales. Good or desirable physical form is a state that does not limit the achievement of good or desirable ecological condition.

Data collected from bioassessment surveys (e.g. fish, diatoms, and invertebrates) are often difficult to interpret without the aid of contextual information concerning physical form. For example, a stream with a mud bed would have a different invertebrate community compared to a stream with a cobble bed, even though both streams might be of a similar size and found in similar parts of a catchment. Similarly, some measured aspects of the flora and fauna are scale dependent, so it is desirable to have available basic information describing the physical setting of the surveyed site. Some geomorphological data may be useful for developing a physical form indicator for inclusion in a multi-metric index of river health, while other data might be used only as contextual information to help interpretation of biological indicator data.

The YRCC management objectives for the lower Yellow River emphasise maximising channel capacity, lowering the bed level, and transporting sediment out of the river channel system. The main objective of these goals is to reduce flood risk, although there is also a benefit provided in supply of sediment for maintaining expansion of the delta.

7.2 Potential indicators

7.2.1 Indicator categories

In wadeable streams, small-scale features of the physical form such as undercut banks, riffles, pools, and cascades provide a range of physical habitat elements. Variability of the bed and bank morphology imparts a significant heterogeneity to the hydraulics of the flow, which also provides a range of habitat types. In a very large river like the lower Yellow River, which has relatively uniform morphology and bed material, the degree of variability of the physical form may not be limiting to river health. Any relationships that exist between aspects of physical form and the health of fish, invertebrates, birds and their habitats would likely be subtle and difficult to measure. An exception is possibly the braided channel form in reach 1, which is likely to offer a greater range of physical habitat opportunities than the channelised reaches downstream to the delta. The IFH incorporated this to some extent because the environmental flows assessment was, in part, based on an assessment of the hydraulic habitat available in the reaches. Overall, for the lower Yellow River, physical form is probably better considered among the indicators of social value than those of ecological value. The exception is the delta, where progradation of the delta area is important for maintaining the vegetation succession process (see Gippel et al. 2012a).

In the lower Yellow River, the physical form is of vital importance with respect to flood risk. The capacity of the channel is a determinant of flood hydraulics, and hence the likelihood of flooding for a given discharge. Also, the capacity of the channel can limit the maximum magnitude of the annual water-sediment discharge regulation event. For much of its length, the bed of the lower Yellow River is perched higher than the surrounding plain, which greatly elevates the consequences of a flood that overtopped the flood protection dikes (see Gippel et al. 2012a).

Considering the main management objectives for the river, there are six main categories of potential physical form indicator:

- bank stability (stable to minimise contribution of sediment that would build up the river bed)
- bed elevation (should not rise, to contain flood risk)
- channel capacity (large enough to facilitate sediment transport events)
- annual sediment load (to maintain growth of delta area)
- sediment concentration during sediment transport events (high enough for the bulk of the sediment to be deposited on the delta lobes)
- relative area of the delta (with growth being desirable).
7.2.2 Bank stability

Bank erosion is undesirable on the lower Yellow River because of the additional sediment it contributes to the channel, which is already perched from sediment over-supply. The river banks are now largely fortified against erosion by training works. This has led to a dramatic reduction in movement of the channel (Wu et al. 2005, Figure 35). The success in stabilising the majority of the river channel means that this would not be a sensitive indicator. Also, while there are many cross-sections along the river that are repeat surveyed each year, they are not aligned perpendicular with the channel, so it would be difficult to measure channel change from these data.

Figure 35. 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).

7.2.3 Relative bed elevation

The bed elevation is a critical determinant of flood risk. It is important enough to be included as one of the ‘4 nos’ of (Li, 2004). Every year YRCC surveys 370 monumented transects across the river. These data could be used to assess the relative elevation of the bed. The method would involve extracting the lowest elevation from each cross-section and then plotting this as a thalweg profile (elevation versus distance downstream). Comparing the elevation along the river from one year to the next would indicate where, and to what extent, the river bed rose or fell relative to its elevation in the previous year, or relative to its elevation in a benchmark year, such as 2001, just prior to initiation of the annual WSDR events. A physical form indicator could be developed for each of the four reaches by calculating the average thalweg elevation along each reach. As long as the elevation was lower than the 2001 elevation, the index value should be positive. A scale would have to be devised relative to the expected degree of bed lowering each year.

While relative bed elevation is an important indicator, its measurement relies on availability of all cross-section data for each year of survey. While some of these data were available to the project, without the full set, including the benchmark year, it was not considered worthwhile to pursue further development of this index.

7.2.4 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 1974–1990, Yue (1996) proposed that the most efficient discharge was 3500 m$^3$/s. 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). Liu et al. (2006) also pointed out that flows in the range 800 to 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. Liu et al. (2006) and Liu and Liu (2009) set the objective
for bankfull capacity at 4000 m³/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 WSOR event for the lower Yellow River.

The bankfull capacity of the lower Yellow River channel has varied significantly over time (Figure 36). 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 36). The bankfull capacity at Lijin, as reported by Ru et al. (2003), followed the same pattern as that observed by Wu et al. (2008) at Huayuankou (Figure 36). 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 36). Bankfull channel capacity is potentially a useful indicator, with a capacity of 4000 m³/s (YRCC target capacity) being an appropriate reference value.

Figure 36. Measured bankfull discharge at Huayuankou, mean daily discharge in the flood season (July to October), and moving average of discharge, from 1950–2003.

Wang et al. (2007) estimated that an annual average sediment load of 3.45 × 10⁸ 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 et al. (2007) (Figure 37). Annual sediment load is potentially a useful indicator, with a minimum of 3.45 × 10⁸ tonnes at Lijin being an appropriate reference value. Since the Xiaolangdi Dam has been in operation, while considerable sediment has been scoured from the channel, large quantities of sediment have been stored upstream in the dam. The target minimum sediment load was only achieved in one year over the period 2000–2007 (Figure 37).
7.2.6 High-flow event sediment concentration

The main objective of the annual WSDR event is to scour sediment from the bed of the lower Yellow River and to transfer this sediment, along with sediment sourced from within Xiaolangdi Reservoir, out of the mouth and onto the delta. Through a significant research effort, the YRCC have developed a good understanding of the hydraulics of sediment transport in the lower Yellow River. A number of different estimates have been made regarding the optimum concentration of sediment for maximising sediment load (see Gippel et al. 2012a). However, one critical aspect of sediment transport is ensuring that the sediment flows out of the river mouth and then deposits on the delta lobes rather than travelling a long distance into the Bohai. The suspended sediment from low concentration surface layers travels a long way, gradually but progressively falling to the sea floor (Wright et al. 1986). In contrast, extremely high suspended sediment concentrations favour hyperpycnal plumes (underflows) that produce precipitous deposition and 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 the 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 three 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 biogeochemical cycles in the estuary and to sustain the pattern of delta building.

Based on the understanding of the process of delta building, the target sediment concentration during the WSDR event is >35 kg/m$^3$. 

---

**Figure 37.** Annual sediment load and discharge at Lijin (for calendar years) for the period 1956–2007, showing phases of delta change identified by Chu et al. (2006) and the sediment load threshold required for equilibrium of delta area identified by Wang et al. (2007).

Note: 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.
7.2.7 Growth rate of delta area

The growth of the delta provides land for succession of vegetation, and habitats for birds and fish. Historically, the high conservation value of the delta was to a large extent due to the unusually rapid rate of progradation (growth) of the delta seaward. If the delta area contracts, or stabilises, the vegetation succession process will change. The consequence of this for the availability of shore bird habitat is likely to be negative due to a reduction in suitable mudflat. The area of the delta is a response variable, while the sediment transport rate and sediment concentration data are forcing variables.

7.3 Methodology

Consideration of potential physical form indicators suggested two indicator groups and four practical sub-indicator categories:

- **Channel physical form:**
  - bankfull channel capacity

- **Delta physical form:**
  - annual sediment load to the delta
  - sediment concentration during the WSDR event
  - growth rate of delta area.

The channel physical form group belongs with the social indicators in relation to flood risk, while the delta physical form group belongs with the environmental indicators (Note: Some sub-indicators comprised a number of components. Figure 4).

7.3.1 Bankfull channel capacity

Index based on discharge as a surrogate for channel capacity

In the lower Yellow River, Wu et al. (2008) established a relationship between discharge in the flood season and channel capacity, with discharge in previous years partly determining the channel capacity of the current year (Figure 36). The models of Wu et al. (2003) indicated good predictive power, but require sediment concentration data, which is not always readily available.

The moving average of mean daily discharge in the high flow period (July to October) was correlated with channel capacity at Huayuankou \( (C_n) \), using the data of Wu et al. (2008) from the period 1959–2001 (i.e. before operation of the WSDR). The length of time over which the moving average of discharge was calculated was progressively increased. This revealed that the highest correlation \( (R^2 = 0.6549) \) was achieved with the five-year moving average of mean daily discharge in the high-flow period. However, the three-year moving average \( (3yrQ_n) \) had a similarly high correlation coefficient \( (R^2 = 0.6509) \) and was the preferred model, because it is known that the channel capacity responded quite quickly to the WSDR events. The relationship was:

\[
C_n = 1.2462X3yrQ_n + 2775 \quad (22)
\]

This equation implies that to achieve the target channel capacity of 4000 m\(^3\)/s the three-year moving average of mean daily discharge in the high flow season should be at least 983 m\(^3\)/s. For the post-Xiaolangdi period, the high flow season does not necessarily follow the natural high flow period, as the WSDR event is sometimes released as early as June and sometimes as late as November. The four highest continuous months were used to define the high flow period of each year from 1997 to 2008, to give a time series of three-year moving average of mean daily flow in the high flow months from 1999 to 2008. The lowest three-year moving average in the series of Wu et al. (2007) was 443 m\(^3\)/s. For the channel capacity forming flow the minimum was set at 443 m\(^3\)/s (Index of channel capacity flow score = 0) and the maximum necessary to achieve the target channel capacity was 983 m\(^3\)/s (Index of channel capacity flow score = 1). Index of channel capacity flow scores \( (I_{C_n}) \) were assigned to each year \( (i) \) by scaling according to the discharge between this range, with values higher than 983 m\(^3\)/s scoring 1:

\[
I_{C_n} = 0.001876X3yrQ_n - 0.8443 \quad (23)
\]
Index based on direct measurement of channel capacity

The index defined by Equation (23) is convenient as a channel capacity index, because its calculation requires only monthly discharge data. Relationships of this form could be applicable in river situations where channel capacity is not routinely directly measured. However, direct measurement of channel capacity is always preferable to using a discharge index as a surrogate. In the lower Yellow River, channel capacity is such a high priority issue for YRCC that channel capacity is measured annually at key gauging stations by rating the gauges at the time of the annual WSDR event. An annual estimate of channel capacity was available for the period 2002–2010 for the gauging stations Huayuankou, Jiahetan, Gaocun, Sunkou, Aishan, Luokou, and Lijin.

An index of channel capacity ($CC_i$) was developed on the basis of observed over expected, where the expected is the management target. In the lower Yellow River the current target is 4000 m$^3$/s, but it would be useful to have an index that continued to apply in the long-term when capacity increased beyond 4000 m$^3$/s. The historical data of Wu et al. (2008) and Ru et al. (2003) (Figure 36) suggest that channel capacity at Huayuankou could reasonably be as high as 8000 m$^3$/s and at Lijin at least 7000 m$^3$/s. On this basis, the long-term expected maximum capacity was set at 7000 m$^3$/s for all gauges. The equation for the channel capacity index is:

$$CC_i = \frac{C_O}{C_T},$$

where

- $C_O$ = observed channel capacity in year $i$ in 10$^8$ m$^3$/s
- $C_T$ = channel capacity target; $C_{T1}$ = 4000 m$^3$/s (current target); $C_{T2}$ = 7000 m$^3$/s (expected long-term maximum).

7.3.2 Annual sediment load to delta

The load of sediment to the delta (reach 4) is measured at Lijin gauging station. The importance of sediment transport as a management objective means that the TSS concentration has been routinely measured by YRCC for many years. Annual suspended solids load data for Lijin were available from YRCC for the period 2006–2010, and data prior to that were published by Miao et al. (2010) (Figure 37).

Chu et al. (2006) identified three periods of change in the area of the delta (Figure 37):
- 1975–1984: rapid progradation

Over these three periods, the annual sediment load at Lijin averaged 8.91, 5.35, and 2.55 10$^8$ tonnes, respectively. Wang et al. (2007) estimated that an annual average sediment load of 3.45 10$^8$ tonnes of sediment at Lijin would maintain (at equilibrium) the delta coastline of the Yellow River estuary. This information suggests a scale for an index of annual sediment load for delta maintenance. The minimum load is 3.45 10$^8$ tonnes, and the reference (target for ensuring rapid progradation of the delta) is 8.91 10$^8$ tonnes. A load of 3.45 10$^8$ tonnes does not warrant a score of zero because if the delta area was stabilised in the long-term, it would still have positive (if different) ecological values. However, this load does not warrant a score of 1, because rapid progradation provides higher ecological values than a stable area. Therefore, a load of 3.45 10$^8$ tonnes was assigned a score of 0.2 (a value based on expert opinion), and any load less than 3.45 10$^8$ tonnes was awarded a score of zero, because a persistent trend of annual net loss would ultimately lead to loss of the delta. A load of 8.91 10$^8$ tonnes or higher was assigned a score of 1. The average load in the period 1985–1995, which was characterised by progradation and erosion, would score 0.5.

The score for the annual sediment load index for any year ($SL_i$) was estimated as:

$$SL_i = 0.1465 S_i – 0.3055, \quad \text{for } 3.45 < S_i < 9.81$$

$$SL_i = 1, \quad \text{for } S_i \geq 8.91$$

$$SL_i = 0, \quad \text{for } S_i \geq 3.45$$

where

$S_i$ = annual sediment load at Lijin for year $i$ in 10$^8$ tonnes.
7.3.3 Sediment concentration during high flow event

As noted previously, suspended sediment concentration is sampled both monthly, and more frequently under high flow event conditions. Only the monthly data were available to this project, but if the sediment concentration index is adopted as part of a river health index for the lower Yellow River, then it is recommended to use the more frequently sampled data.

The high flow event sediment concentration index ($SC_i$) for any year was calculated using Equations (28), (29) and (30) as the per cent of the annual sediment load at Lijin that was delivered under conditions of the concentration exceeding the critical threshold for hyperpycnal plume formation, which 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$^3$ (Wang et al. 2010). The value of 65 per cent was adopted as the reference value for this index, with a score of zero if no sediment was delivered at this threshold concentration or higher [Equations (28), (29) and (30)]:

\[
SC_i = \frac{SL_{35^+}}{0.65}, \text{ for } SL_{35^+} < 0.65 \tag{28}
\]

\[
SC_i = 1, \text{ for } SL_{35^+} \geq 0.65 \tag{29}
\]

\[
SC_i = 0, \text{ for } SL_{35^+} = 0 \tag{30}
\]

where $SL_{35^+} =$ proportion of annual sediment load in year $i$ delivered at a concentration exceeding 35 kg/m$^3$.

7.3.4 Growth rate of delta area

The area of the delta was measured from Landsat TM/ETM+ images from four dates, as detailed in a previous section of this report. A delta growth index was calculated using Equations (7), (8) and (9).

7.4 Results

7.4.1 Bankfull channel capacity

Since implementation in 2002 of the policy of an annual WSDR event, the channel capacity of the lower Yellow River has progressively increased at each gauge on the river (Figure 38). The index of channel capacity based on the current target of 4000 m$^3$/s (Equation (24)) indicated high scores for all stations not long after the WSDR policy had been in operation. Using the long-term expected maximum channel capacity in Equation (24) indicated that Huahyuankou is already close to that value, and at other locations the channel capacity is trending upwards (Figure 38). These data clearly indicate that the WSDR has been successful in achieving the aim of 4000 m$^3$/s channel capacity.

The bankfull channel capacity was estimated at a number of places along the river, but it is the point with the lowest capacity that limits the maximum discharge that can be transferred down the river. In recent years, the critical location is Sunkou (Figure 38). The index score from Sunkou was used to represent the entire lower river.

7.4.2 Sediment load to delta

In the 13-year period 1997 to 2010, the sediment load at Lijin exceeded that required for progradation of the delta in only two years (Figure 39). Those years, 1998 and 2003 were the only years to score a positive value for the sediment load index (Figure 39).

7.4.3 Sediment concentration during high flow event

The annual high flow event sediment concentration index was calculated for Lijin over the period 1994 – 2008 (with sediment concentration data unavailable in 2000 and 2001) using monthly sampled data (Figure 40). The data indicated that sediment concentration exceeded the threshold concentration for hyperpycnal plume formation (35 kg/m$^3$) in only two years of the period investigated, in 1996 and 2005 (Figure 40). A different pattern would have emerged had higher frequency sediment concentration data been available, with the other years more likely to have shown a positive index value.

7.4.4 Delta growth rate

From 1997 to 2002 the area of delta growth was less than the area eroded due to low river flows and sediment loads and erosion of the original southern Qingshui channel (see Gippel et al. 2012a). Since 2002 (post-Xiaolangdi Dam), implementation of the annual water-sediment discharge event regulation has reversed this trend and increased the rate of delta progradation (Huang et al. 2007). The area of the delta changed positively between 2002 and 2006 (Figure 41). The delta growth index ($ID_j$) was calculated using Equations (7), (8) and (9). The index was positive for 1997 and 2006, but loss of area between 1997 and 2002 gave a score of zero for 2002 (Figure 41).
Figure 38. Time series of measured channel capacity and channel capacity index at seven gauges on the lower Yellow River since implementation of the WSDR policy in 2002.

Note: Top plot shows the measured channel capacity; the middle plot shows the channel capacity index using a target capacity of 4000 m³/s; the bottom plot shows the channel capacity index using an expected maximum capacity of 7000 m³/s.
Figure 39. Annual sediment load at Lijin for the period 1994-2008. Data from 1995 – 2005 from Miao et al. (2010); data for more recent years data from YRCC.

Figure 40. Annual high flow event sediment concentration index time series (for Lijin).

Figure 41. Change in area of Yellow River Delta over time, measured from Landsat imagery, and delta growth rate index.
7.4.5 Delta physical form river health score

Four physical form sub-indicators were evaluated: bankfull channel capacity flow ($\text{CC}_i$); annual sediment load ($\text{SL}_i$); high flow event sediment concentration ($\text{SC}_i$); and delta growth rate ($\text{ID}_i$). The bankfull channel capacity index was assigned to the social indicators group, while the delta-related indices were assigned to the environmental indicators group (Figure 4).

Scores were only available for the delta growth rate index for three years: 1997, 2002 and 2006. Data on the annual sediment load and high-flow event sediment concentration indices were available for the period 1994–2008. The delta growth rate index measures the response of the delta to the sediment delivered to the mouth of the river, which is dependent on river sediment load and high flow sediment concentration (the rate of marine erosion also determines delta area, but it was not measured here). A combined annual delta physical form index ($\text{PF}_{Di}$) was calculated for each year ($i$) based on the two forcing variables, with the result compared with the delta growth rate. The two sub-indicators were not weighted:

$$\text{PF}_{Di} = \frac{\text{SL}_i + \text{SC}_i}{2} \quad (31)$$

The delta physical form indicator (Figure 42) suggests that conditions were not conducive to delta progradation since Xiaolangdi Dam was constructed in late-1999. The dam traps a significant percentage of incoming sediment, and the sediment scouring from the channel downstream, while certainly leading to an improvement in channel capacity, is insufficient to ensure ongoing maintenance or growth of the delta (Figure 42). Analysis of satellite imagery suggests the delta grew between 1984 and 1997, when the delta physical form index was moderate (~ 0.5 for the entire period) (Figure 42). From 1997–2002, the delta physical form index was low, and the delta area declined (Figure 42). The delta grew slightly between 2002 and 2006, which could have been related to a relatively high sediment load in 2003, or favourable conditions for formation of a hyperpycnal plume in 2005 (Figure 42). Since then, conditions have not been favourable for delta growth (Figure 42). These results highlight the importance of annual monitoring of the surface area of the delta.

Figure 42. Combined physical form index over the period 2003–2008, compared with delta growth index measured in 2002 and 2006.
Chapter 8. Social Health

The social health component of the river health assessment for the lower Yellow River was principally undertaken by Fu Xinfeng from Yellow River Institute of Hydraulic Research, Yellow River Conservancy Commission, Zhengzhou. This section of the report comprises edited extracts from Fu (2010). More detail can be found in the original report.

8.1 Rationale for inclusion

The policy framework for management of the Yellow River formulated by Li (2004) includes both social and ecological health as management objectives, so there is a need to be able to quantify social river health. In this report, the term ‘social river health’ means the condition of a river with respect to the cultural, social and economic values that are derived directly from the river.

The social targets for the lower Yellow River centre on flood protection, no interruption to water supply, and meeting water quality standards for human needs (Li, 2004; Liu et al. 2006). Within the YRCC (and probably elsewhere in China) the policy for managing river-derived social benefits is integrated with that for achieving ecological health. This is partly because in rivers with a high level of competition for scarce water resources, managers routinely balance the likely social benefits against potential ecological benefits when making water allocation decisions, so they need to have an awareness of the trade-off involved. The other reason for the close association between social and environmental river values in the lower Yellow River is the very long history of human dependency on the river’s resources for protein (fishery, now virtually non-existent); domestic water supply; agriculture; transport; and more recently for industry. The capacity of the river to provide these resources was partly dependent on its ecological health. The risk of flooding has always been an over-riding concern of people living near the lower Yellow River.

A poorly managed river has potential to improve in both ecological health and social health. In a river with high demand for water resources, at some point, a marginal increase in ecological health will result in a marginal loss of social health, and vice-versa. The lower Yellow River is currently at the point where potential water demand exceeds supply (Xi et al. 1996; Zhang et al. 1999; Xu et al. 2002; Jiang et al. 2004). The goal of management of the lower Yellow River is to maintain the river in the state when both social and ecological benefits are maximised. One necessary requirement for achievement of this state is the ability to measure both the ecological health, and the social health, of the river. Measurement of social river health is the subject of this section.

8.2 River-dependent social values

8.2.1 Social river health indicators

Very little specific reference is made in the literature to social river health indicators. Karr (2005) wrote that:

‘...society needs comprehensive, integrative, and easily interpreted indicators of both social and ecological well-being, that is, indicators reflecting the health of living, biological systems, human and nonhuman…. If …we couple improved biological indicators with carefully defined social indicators and better economic indicators, we may improve the state of the biosphere as well as our own lives.’

Karr (2005) noted that three common measures of social health – child poverty, high school completion, and health insurance – were good indicators of overall social health. However, these have no direct dependence on river health.

Vemuri (2004) provided evidence to suggest that the natural river environment does have a contribution to make to human satisfaction levels and to quality of life as a whole. Specifically, the natural environment (including rivers) has a direct relationship with neighborhood satisfaction and mainly an indirect relationship with life satisfaction.

To complement indices of ecological river health, Cary and Pisarski (2009; 2011) developed a social benchmarking instrument to measure community dispositions and behaviour regarding river health in Victoria, Australia. The aims were to:

1. provide a benchmark of the social condition of communities’ attitudes, values, understanding and behaviours in relation to river health
2. provide information for developing management and educational priorities
3. provide the basis for assessment of the long-term effectiveness of community communication and education activities in achieving changes in attitudes, understanding and behaviours in relation to river health.

Similarly, Metcalfe and Riedlinger (2009) identified four indicators to test the social condition of the public in Victoria, Australia with regard to river health. These indicators were river use, river knowledge and literacy, values and aspirations, and river health behaviours. The main application of these indicators was community engagement and
science communication programs about river health. Cary and Pisarski and Metcalfe and Riedlinger collaborated to develop a Social Index of Stream Condition for Victoria (Pisarski et al. 2008). This index is mainly a tool to assist government to more effectively communicate to individuals and communities information about river health to increase the ecological benefits of investment in river health. While this index is of interest, it is different to the main purpose of developing a social river health index for the lower Yellow River.

8.2.2 Valuing ecosystem services provided by rivers and wetlands

Costanza et al. (1997) estimated the current global economic value of 17 ecosystem services for 16 biomes, based on published studies and a few original calculations. Globally, the services provided by freshwater wetlands were worth USD3.2 trillion annually, while those provided by lakes and rivers were worth USD1.7 trillion.

De Groot et al. (2010) estimated the monetary values of ecosystem services provided by 11 biomes, which included rivers and lakes, and inland wetlands biomes. De Groot et al.’s (2010) methodology identified 22 ecosystem services that were potentially provided by the biomes (Table 15). Based on 86 data points, the total monetary value of the potential sustainable use of all ecosystem services provided by the Inland wetlands biome combined varied between 981 and 44,597 Int.$/ha/yr. Based on 12 data points, the total monetary value of the potential sustainable use of all ecosystem services provided by the Rivers and lakes biome combined varied between 1,779 and 13,488 Int.$/ha/yr. The estimates of Costanza et al. (1997) fit within these ranges, being freshwater wetlands valued at 19,580 $USD/ha/yr and rivers and lakes valued at 8,498 $USD/ha/yr.

De Groot et al. (2010) combined information from a number of sources to estimate the annual value of ecosystem services provided by the River Murray, Australia at $AUD 4.7 billion (Table 16). Food produced from irrigation and tourism and recreation services along the river accounted for the majority of the economic value. Other values are the avoided damages provided by maintaining low salinity levels, and the provision of environmental flows to maintain aquatic habitat.

Table 15. Categories of ecosystem services provided by rivers and wetlands.

<table>
<thead>
<tr>
<th>Service Group</th>
<th>Potential ecosystem service</th>
<th>Services used in estimating values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Inland wetlands</td>
</tr>
<tr>
<td>Provisioning</td>
<td>Food</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>(Fresh) water supply</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Raw materials</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Genetic resources</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Medicinal resources</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Ornamental resources</td>
<td>✓</td>
</tr>
<tr>
<td>Regulating</td>
<td>Influence on air quality</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Climate regulation</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Moderation of extreme events</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Regulation of water flows</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Waste treatment / water purification</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Erosion prevention</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nutrient cycling and maintenance of soil fertility</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Pollination</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biological control</td>
<td></td>
</tr>
<tr>
<td>Habitat services</td>
<td>Lifecycle maintenance (esp. nursery service)</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Gene pool protection (conservation)</td>
<td>✓</td>
</tr>
<tr>
<td>Cultural services</td>
<td>Aesthetic information</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Opportunities for recreation and tourism</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Inspiration for culture, art and design</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Spiritual experience</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Cognitive information (education and science)</td>
<td>✓</td>
</tr>
</tbody>
</table>

Source: de Groot et al. (2010).

1 The International dollar is a hypothetical unit of currency that has the same purchasing power that the US dollar had in the United States at a given point in time. Here, the reference year is 2007.
Table 16. Total annual economic value of ecosystem services provided by the River Murray, Australia (2007 $AUD/Year).

<table>
<thead>
<tr>
<th>Ecosystem Service</th>
<th>Valuation method</th>
<th>Source</th>
<th>Total value ($million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recreation and tourism</td>
<td>Market prices</td>
<td>Howard (2008)</td>
<td>2970</td>
</tr>
<tr>
<td>Food production</td>
<td>Market prices</td>
<td>ABS (2008)</td>
<td>1600*</td>
</tr>
<tr>
<td>Water quantity (environmental flows)</td>
<td>Contingent valuation</td>
<td>Bennett (2008)</td>
<td>80</td>
</tr>
<tr>
<td>Water quality (no salinity)</td>
<td>Avoided cost</td>
<td>Connor (2008)</td>
<td>18</td>
</tr>
<tr>
<td>Total Economic Value</td>
<td></td>
<td></td>
<td>4668</td>
</tr>
</tbody>
</table>

An estimate for the River Murray water only. Total value of irrigated agriculture in the Murray–Darling Basin is AUD4600 million. Water drawn from the River Murray for irrigation is approximately a third of the total water drawn from the basin. Source: de Groot et al. (2010).

O’Connor (2010) identified and quantified the economic benefits from the restoration and protection of healthy wetlands in the Murray–Darling Basin, Australia, using as a case study the Hattah wetlands, a Ramsar-listed wetland within the Hattah-Kulkyne National Park in northern Victoria. As well as being an internationally important habitat area for birds, the lakes have long provided natural flood mitigation, storing excess run-off from flooding events that are then slowly released back into the river system or evaporate. The lakes are also important in managing the flows of excessive sediment and nutrients that occur in flood events (O’Connor 2010).

O’Connor (2010) used the method of Total Economic Value (TEV). TEV is a method for measuring the total range of economic values attributable to an environmental asset, including the ecosystem services they provide, and consists of the following categories (Figure 43) (DEST 1995; O’Connor 2010):

• **Direct use value**
  Includes consumptive uses (i.e. provision of goods, such as timber, hunting, fishing etc.) and non-consumptive uses (i.e. non-extractive cultural uses such as recreation and tourism). These values are associated with monetary values through market prices.

• **Indirect use value**
  The value of the ecosystem services provided by the natural asset. In the case of wetlands this includes water filtration, flood protection, water storage, groundwater recharge, nutrient discharge, carbon storage as well as habitat.

• **Option value**
  The value placed on conserving an environment for future use, i.e. having the option to use it at a later time (option) or by future generations (bequest).

• **Existence value**
  The satisfaction people gain by simply knowing a natural asset exists, even if they never plan to use it.

The study found that Hattah Lakes provided an annual economic value of AUD $14.7 million. Of the total value $10.71 million value was associated through direct non-consumptive use (tourism and recreation), $3.85 million value was provided through indirect use (water filtration, flood control, water storage and habitat), and the willingness of people to pay to protect the wetlands was valued at $0.13 million.

Dyack et al. (2007) assessed the recreational values at Barmah Forest and the Coorong, two Ramsar-listed wetland sites on the River Murray, Australia. The approach taken was to estimate the non-market benefits associated with the recreational visits (Figure 43). Values were expressed in terms of consumer surplus (willingness to pay), which is a measure of the value of consumption. Three methods were used: the travel cost method (TCM) and the contingent valuation method (CVM) were used to estimate the consumer surplus of recreation trips, while the contingent behaviour (CB) approach was used to estimate the responsiveness of visits to changes in access as well as to estimate the change in value caused by changes in access. The TCM is a revealed preference technique, where the investment of recreational users in travel costs and time is used to assess the value of the recreational experience (Dyack et al. 2007). The CVM and CB approaches are stated preference techniques, where recreational users are directly asked about the value of their recreational experience or their response to potential changes in condition (Dyack et al. 2007). Using the TCM results, the total annual value of recreation at Barmah Forest was estimated to be $AUD 13 million (25,000 Ï $529/adult visitor). The corresponding estimate for the Coorong was $AUD 57 million (112,500 Ï $503/adult visitor).
Hassall & Associates and Gillespie Economics (2004) undertook an evaluation of the market and non-market value of river-dependent non-consumptive industries (i.e. those other than irrigated agriculture and urban water) (Figure 43) in the Southern Murray–Darling Basin (Murray, lower Darling, lower Goulburn, Mitta Mitta and Murrumbidgee Rivers). This was primarily a desktop study that used existing information, but some primary data were collected from real estate groups, boating and recreational associations, state tourism bodies and state fisheries bodies (the key non-consumptive industries were tourism and recreation, real estate and fishing).

The estimate of the economic value of non-consumptive industries that are dependent, or partially dependent, on healthy rivers in the Southern Murray Darling Basin was in the order of $AUD1.62 billion. This estimate was a present value figure. The greatest economic values were associated with:

- amenity
- camping and caravan parks
- recreational fishing
- commercial and non-commercial boating.

The study recognised that non-use values associated with river health (i.e. options, bequest and existence values) (Figure 43), which were not evaluated in the study, may be worth significantly more than the use values (Hassall & Associates and Gillespie Economics, 2004). Furthermore, all use activities that involve expenditure in the region add to the regional economic activity by way of increased output, value-added, income and employment (Hassall & Associates and Gillespie Economics, 2004).


Present value is the current value of the expected future economic values. A 5 per cent discount rate is used to convert future annual values to today’s dollars.
8.2.3 Relationships between river health and social indicators in the lower Yellow River

A few studies have indicated the existence of an inverse relationship between ecological river health and social river health on the lower Yellow River. Declining ecological health, represented by water quality and hydrological measures, has been associated with increases in agricultural activity, population, industrial production and GDP (gross domestic product). However, other data demonstrates that the relationship is not linear, because in the 1990s river health declined to the point where significant economic and social costs were incurred. Uncontrolled floods are also associated with high social and economic costs.

Water quality and social health

The data of Chen et al. (2004) show how nitrogen concentration in river water at all Yellow River basin sampling stations, including Luokou on the lower Yellow River, increased significantly between 1960 and 2000. 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 nitrogen concentration occurred at all stations in 1990 to 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).

Yu et al. (2010) examined river water nitrogen 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 an increasing trend in total nitrogen concentration over the period of observation, with step changes in the early 1980s and early 1990s at Huayuankou and a step increase in the early 1990s at Luokou and Lijin. 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. 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 fertiliser 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.

Cease to flow and social health

The lower Yellow River began to experience significant cease to flow events in the 1970s. During the periods of cease to flow in the 1990s, water was not available to industry, and various enterprises and oilfields had to suspend production. Losses of 200 million RMB per year were sustained during the 1970s and 1980s, rising to 4 billion RMB per year in the 1990s (Liu and Zhang 2002). Chang (2001, as reported in Wang et al. 2008) reported the average yearly loss caused by drying of the river alone was nearly 1.4 billion RMB.

Between 1972 and 1996, in the lower Yellow River, the economic losses of industry and agriculture caused by water resources shortage and drying of the river totalled 26.8 billion RMB (Chang, 2001, reported in Wang et al. 2008). Liu and Zhang (2002) reported that the loss amounted to 40 billion Yuan, and Xu (2001) reported a loss of US$10 billion (~70 billion Yuan) since 1990.

The periods of cease to flow in the 1990s caused losses in cereal production of 1.3 million tonnes, giving an economic loss of 1.6 billion RMB. In an exceptionally dry year, drying up of the river caused a maximum agricultural production loss of more than 3 billion RMB (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 every day to fetch water from appointed public water taps (Liu and Zhang 2002).

Floods and social health

The most recent large flood in the lower Yellow River occurred in 1998. This flood affected 7.33 million houses, caused 3,656 deaths, affected 25 million hectares of farmland, resulted in monetary losses estimated at RMB 248.4 billion (USD30 billion equivalent) and reduced gross domestic product (GDP) by 3–4 per cent (ADB, 2001). Two years before, in 1996, a flood affected 5.12 million houses, caused 4,400 deaths, impacted 31 million hectares of farmland, resulted in monetary losses of RMB 220.8 billion (USD26.7 billion), and reduced GDP by about 4 per cent (ADB, 2001).
8.3 Potential indicator categories

TEV studies of the ecosystem services of wetlands and rivers provide useful information for a social river health index. However, these studies tend to be one-off investigations, and the methods may not be practical for annual assessments. Also, TEV studies reviewed here report an estimate of absolute value, and do not use the concept of a reference, or expected value, which would be required for river health reporting.

Fu (2010) attempted to value the recreational use of the Mengjin, Huayuankou, Kaifeng, and delta wetlands using a TEV framework (Figure 43). The research examined ticket prices, money spent on recreation, visitor numbers, and an estimate of existence value. This work was only undertaken at a preliminary level, and could not achieve a reliable annual estimate of the value of these wetlands due to lack of basic information on how people value wetland assets in China, and the difficulty in obtaining visitor numbers. However, this approach has potential as a social health indicator because the factors that determine wetland value would vary from year to year. Examples of such variables are visitor numbers, ticket prices (corrected to a price index), total expenditure on the tourism experience (which would likely increase with development of facilities and marketing of the experience), and the existence value that people place on wetlands (which would likely increase the more people had a positive experience, and the more this value was promoted by government agencies and the education sector). A difficulty in scoring the value of recreational use of wetlands, even if an annual value could be reliably and simply measured, is the lack of an obvious reference value. Perhaps the reference would have to be an aspirational target determined by the relevant authorities with advice from representatives of the tourism industry.

Based on the review of literature, the socio-economic character of the lower Yellow River, and the management priorities of YRCC, seven potential indicator categories were evaluated for their utility in characterising the river-dependent social benefits of management of the lower Yellow River:

- flood risk – due to storm event and ice jam
- drought risk
- water consumption
- water quality
- hydropower
- navigation.

The indicator categories represent the provisioning and regulating service groups identified by de Groot et al. (2010) (Table 15). Most of the social river health indicators applied to the entire length of the lower Yellow River, rather than applying to the four reaches defined for river health assessment. There was only a single social river health score for the entire study area.

8.4 Methodology

8.4.1 Flood risk index

A major flood with dike breach imperils 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 is highly vulnerable to floods, makes up 85 per cent of the lower river catchment area and has a population of 1.7 million residents living in 2,193 villages (Gippel et al. 2012a). Minimising the flood risk to these people is one of the most important services provided by the YRCC in managing the lower Yellow River.

Flood risk is a function of the:

- pattern of rainfall and ice formation
- available air space (storage capacity) in the upstream reservoir
- available storage area in the flood detention basins
- capacity of river channel
- relative safety of the flood dikes.

The safety of the flood dikes was upgraded in association with the construction of the Xiaolangdi Dam, so is assumed to be high, and unchanging from year to year. There are two major flood detention basins on the lower Yellow River: Beijingdi flood detention basin, between Huayuankou and Sunkou, and Dongping Lake flood detention basin. These basins are intended for emergency use only, so their capacity is unchanging from year to year. The Xiaolangdi Dam has a set volume allocated for flood storage, so once again, this variable is unchanging from year to year, although in the long-term, excessive sedimentation could lower the flood storage capacity. Rainfall is not controllable through regular management activities so cannot be included in a flood risk index. This leaves one main variable for characterising the risk of floods associated with storm events – the capacity of the river channel.
The storm event flood risk index \( FS_i \) is, from Equation (24):

\[
FS_i = CC_i = \frac{C_O}{C_{C2}}, \quad \text{for} \quad (32)
\]

where

\[
C_O = \text{observed channel capacity in year } i \text{ in } 10^8 \text{ m}^3/\text{s},
\]

\[
C_{C2} = 7000 \text{ m}^3/\text{s} \quad \text{(expected long-term maximum capacity)}.
\]

The lower Yellow River commonly freezes over in winter with the downstream, higher latitude, sections most prone to ice (see Gippel et al. 2012a). From Huayuankou to Gaocun flowing ice dominates, and the probability of freezing is less than 20 per cent. 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 (see Gippel et al. 2012a).

The ability to control the river’s flow by dams has changed the ice regime of the Yellow River (Ye et al. 1999; Qian et al. 2007). Prior to regulation, 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). Over the period 1951 to 1990, the maximum length of river that would freeze was about 700 km, and the minimum length was about 25 km. Sammenxia 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 Sammenxia 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 et al. (2007) claimed that operation of the 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 (see Gippel et al. 2012a).

Empirical models have been developed to relate ice regime based on air temperature and ice density. Other models are based on thermodynamic, river hydraulics and practical experience (Ye et al. 1999). The YRCC has available good predictive power with respect to ice flood control. A comprehensive ice prevention index for the lower Yellow River would involve an estimate of the river’s capacity to store accumulated ice, the speed of the floating ice and the unfrozen (sub-ice) capacity of the river. Given the difficulty in estimating these parameters, a simple ice flood risk index \( FI_i \) was developed on the basis of the longest extent of the river that is frozen \( FI_{iL} \), and the river discharge in the ice flood risk season \( FI_{iQ} \), with the discharge being weighted twice as important as the length of river under ice.

\[
FI_{iL} = 1 - \frac{FI_{OL}}{FI_{IL}}, \quad \text{or} \quad 1 \text{ if } FI_{OL} > FI_{IL} \quad (33)
\]

\[
FI_{iQ} = 1 - \frac{FI_{OQ}}{FI_{EQ}}, \quad \text{or} \quad 1 \text{ if } FI_{OQ} > FI_{EQ} \quad (34)
\]

\[
FI_i = 0.25 FI_{iL} + 0.75 FI_{iQ} \quad (35)
\]

where

\[
FI_{OL} = \text{the observed length of frozen river in year } i
\]

\[
FI_{IL} = \text{the length of river susceptible to freezing (400 km – based on YRCC experience)}
\]

\[
FI_{OQ} = \text{the observed discharge on the day of maximum frozen length of river in year } i
\]

\[
FI_{EQ} = \text{the expected maximum discharge in ideal circumstances in the ice flood season (350 m}^3/\text{s – based on YRCC experience)}
\]

A combined flood risk index \( F_i \) was derived by weighting the storm event flood risk index \( FS_i \) as being twice as important as the ice flood risk index \( FI_i \), because the storm event flood affects the entire river length, while ice-flood affects about half the length:

\[
F_i = 0.25 FI_i + 0.75 FS_i \quad (36)
\]
8.4.2 Drought risk index

To ensure water for people, production and ecological use, in June 2007 the Flood Control and Drought Relief
Headquarter of Yellow River (FCDRHYR) was approved to be founded by the State Flood Control and Drought Relief
Headquarters (SFCDRH). According to the rules of the *Ordinance on Yellow River Water Volume Regulation* and the
requirement of SFCDRH to consider drought control, FCDRHYR promulgated implementation of the trial Yellow River
Basin Drought Control Plan. The plan divided the water and drought regime of the Yellow River basin and water supply
zones into three types:

- a large scale severe drought or city water supply crisis (regional drought) that occurs in the basin and water supply zones
- the water runoff and reservoir storage is much less than normal during the water supplying period, and there is a
  shortage of supply for people, production and ecological use
- a warning flow (i.e. risk of cease to flow) is imminent or has occurred in the mainstream or vital tributary of Yellow River.

These situations generate four warning levels (red, orange, yellow and blue) and corresponding four action levels (I, II,
III, and IV). The drought risk index (Dr) was based on the implementation of these levels of action in year i:

\[ D_r = 1.0, \text{ if action not required} \]  
\[ D_r = 0.8, \text{ if action = level IV (blue)} \]  
\[ D_r = 0.6, \text{ if action = level II (yellow)} \]  
\[ D_r = 0.4, \text{ if action = level II (orange)} \]  
\[ D_r = 0.2, \text{ if action = level I (red)} \]

8.4.3 Water consumption index

Under normal circumstances, the more river water is available for consumption, the stronger is the river’s economic
value. The water consumed is that part of river’s flow that is controllable, which does not flow to the sea, and which is
not consumed by the environment or used for sediment transfer. The water consumed comprises water for domestic
use, industrial production and agriculture inside the Yellow River basin and water supplied to areas outside the basin
(Hebei, Tianjin and Qingdao, and for ecological restoration of Baiyangdian). The water consumption index (WCi) was
devised on the basis of two water consumption figures:

- water transferred outside the basin (for Hebei, Tianjin and Qingdao, and for ecological restoration of Baiyangdian)
  \( W_{Ci(i–b)} \)
- total water consumption in the Henan and Shandong reaches \( W_{Ci(H–S)} \).

In combining the indicators, the total water consumption in the Henan and Shandong reaches \( W_{Ci(H–S)} \) was weighted
twice as important as the water transferred outside the basin \( W_{Ci(i–b)} \):

\[ WC_{i(H–S)} = \frac{WC_{i(H–S)}}{WC_{i(H–S)}} \]  
\[ WC_{i(H–S)} = \frac{WC_{i(H–S)}}{WC_{i(H–S)}} \]  
\[ WC_{i} = 0.25 WC_{i(i–b)} + 0.75 WC_{i(H–S)} \]

where

\( WC_{i(i–b)} \) = the observed volume of water transferred outside the basin in year i
\( WC_{i(H–S)} \) = the expected maximum volume of water to be transferred outside the basin \( 2 \times 10^8 \text{ m}^3 \)
\( WC_{i(H–S)} \) = the observed water consumed in the Henan and Shandong reaches in year i
\( WC_{i(H–S)} \) = the expected maximum water consumption in the Henan and Shandong reaches \( 3.318 \times 10^8 \text{ m}^3 \) in
Henan and \( 7.0 \times 10^8 \text{ m}^3 \) in Shandong).

8.4.4 Water quality index

The official water quality standard of the lower Yellow River is Grade III. This standard will maintain the social use
functions of the river. The method for calculating the index score for water quality was described elsewhere in this
report, and is calculated using Equations (13) to (21). For the social river health index, the annual water quality score
was adopted, with the total score for the lower Yellow River for any year being the average of the annual scores for the
four reaches.
8.4.5 Hydropower index

The production of hydropower at the Xiaolangdi Dam is considered by YRCC to be lower priority than the need to control the outflow from the dam for water supply for domestic, industrial and agricultural uses, and transport of sediment out of the river system. Nevertheless, the energy generated at the dam contributes a social value. A hydropower index ($H_P$) was developed on the basis of the electrical energy produced in year $i$:

$$H_P = \frac{H_{P0}}{H_{PE}}, \quad \text{or if } H_{P0} > H_{PE}$$

where

$$H_{P0} = \text{the observed electrical energy generated (10}^9 \text{ kWh) in year } i$$

$$H_{PE} = \text{the original maximum annual energy generation target at the Xiaolangdi Dam (5.1} \times 10^9 \text{ kWh)}.$$

8.4.6 Navigation index

Navigation is currently not a major value of the Yellow River. Navigation is limited by the shallow depth caused by sedimentation of the channel. Over time, alternative transport systems have been developed, so there is no guarantee that an improvement in navigability would appreciably increase its social value. Nevertheless, a navigation index ($N_V$) was developed on the basis of the navigable length of the river, combined with the maximum weight boat that can travel on the river, in year $i$:

$$N_V = 0.5 N_V L_i + 0.5 N_V W_i$$

where

$$L_O = \text{the maximum observed navigable length of river in year } i$$

$$L_E = \text{the maximum expected navigable length of the river in ideal circumstances}$$

$$W_O = \text{the maximum observed boat weight on the river in year } i$$

$$W_E = \text{the maximum expected boat weight on the river in ideal circumstances.}$$

8.5 Results

For the period 2005–2009, the annual scores for the six sub-indicators (Table 17, Figure 44 and Figure 45) showed no variation for navigation (all low), little variation for hydropower production (all high), moderate variation in flood risk (controlled largely by variation in ice flood risk, as storm flood risk was always good), moderate variation in water consumption (but always high), improving water quality (good at the end of the period), and good scores for drought risk until 2009, when there was a ‘red’ level warning issued.

To form a combined social river health index score, the sub-indicator scores were weighted (Table 17, Figure 45). The weightings were based on the perceived relative importance of the values contributed by the component that the indicator represented. These weightings could be improved by estimating the value contributed by the components in terms of currency, but the necessary data for undertaking this step were not available to this project. Hydropower and navigation were regarded as of minor importance; water quality, water consumption and flood risk were all considered to be of the highest importance; and drought risk was of moderate importance because it is partly related to natural processes beyond the control of management (Table 17).

In the period 2005–2009, the combined social river health score varied over a fairly narrow range of 0.61 to 0.75. This means that in general, the social value of the lower Yellow River is high relative to expectations.
Table 17. Scores for the six social river health sub-indicators and the weighted combined index score, for the years 2005–2009.

<table>
<thead>
<tr>
<th>Year</th>
<th>Weighting</th>
<th>Flood risk</th>
<th>Drought risk</th>
<th>Water consumption</th>
<th>Water quality</th>
<th>Hydropower</th>
<th>Navigation</th>
<th>Combined index score</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>0.25</td>
<td>0.56</td>
<td>1.00</td>
<td>0.69</td>
<td>0.36</td>
<td>0.98</td>
<td>0.05</td>
<td>0.61</td>
</tr>
<tr>
<td>2006</td>
<td>0.15</td>
<td>0.49</td>
<td>1.00</td>
<td>0.91</td>
<td>0.71</td>
<td>1.00</td>
<td>0.05</td>
<td>0.73</td>
</tr>
<tr>
<td>2007</td>
<td>0.25</td>
<td>0.46</td>
<td>1.00</td>
<td>0.77</td>
<td>0.83</td>
<td>1.00</td>
<td>0.05</td>
<td>0.72</td>
</tr>
<tr>
<td>2008</td>
<td>0.25</td>
<td>0.58</td>
<td>1.00</td>
<td>0.79</td>
<td>0.81</td>
<td>1.00</td>
<td>0.05</td>
<td>0.75</td>
</tr>
<tr>
<td>2009</td>
<td>0.05</td>
<td>0.46</td>
<td>0.20</td>
<td>0.90</td>
<td>0.92</td>
<td>0.99</td>
<td>0.05</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Figure 44. Scores for the lower Yellow River social river health sub-indicators for the years 2005–2009.

8.6 Conclusion

The work on social indicators developed a framework for further research into this important component for river health assessment. The data collected suggests that, in general, the lower Yellow River is managed to provide a high level of social values. Future work could fully develop the sub-index for characterising the recreational values provided by the ecological assets.
Chapter 9. Combined River Health Index

The work undertaken for indicators of physical form and social river health should be regarded as preliminary. The physical form indicator was specific to the growth of the delta, and since sediment loads have declined with the operation of the Xiaolangdi Dam, the delta has been in a state of declining area, or risk of declining area. The index that characterised the vegetation health of the delta was suitable for the purpose, but images are not always available for the ideal times, so it might not be possible to measure the index score every year. The social health indicators were the least developed of the indicators suggested in this report. However, the data was sufficient to indicate a high level of social values provided by the river.

A combined environmental river health index was developed for each of the four identified reaches from the indicators for:

- ecology of the channel – combined fish, macroinvertebrates and riparian plants
- hydrology – annual IFH score
- water quality – annual aquatic health score.

The combined environmental river health index scores suggested that hydrology was not the main limiting factor to ecological health of the lower Yellow River (Figure 46). It appears more likely that water quality limits the ecological health.
Chapter 10. Conclusion and Recommendations

10.1 River health in the lower Yellow River

The pilot study used a suite of indicators to assess the ecosystem health of the lower Yellow River. The indicators were grouped into biotic indicators for the channel (macroinvertebrates, fish and riparian plants), biotic indicators for the delta (relative composition of wetland vegetation), water quality indicators (pH, oxygen balance, nutrients, metallic toxicants, non-metallic toxicants), hydrological indicators (environmental flow components), physical form indicators (delta growth), and social health indicators (the value of the social services provided by the river). The indicators within each group were chosen for various practical and theoretical reasons, with one essential requirement being an established link to river health.

The work undertaken for indicators of physical form and social river health should be regarded as preliminary. The physical form index was specific to the growth of the delta, and since sediment loads have fallen with the operation of the Xiaolangdi Dam, the delta has been in a state of declining area, or risk of declining area. The social health indicators were the least developed of the indicators suggested in this report. Although preliminary, the data suggested a high level of social value provided by the river. Future work could fully develop the sub-index for characterising the recreational values provided by the ecological assets.

The combined indicator scores suggested that since the time of implementation of environmental flows on the river, particularly since 2004, hydrology has not been the main limiting factor to ecological health of the lower Yellow River. It appears more likely that water quality limits the ecological health. Application of the river health indicators to historical data clearly demonstrated the enormous improvements made to river water quality and hydrology since the late-1990s. It may take some time before the ecological response to improved hydrology and water quality is reflected in improved biotic health scores.

The methodology developed for this pilot study is open to improvement. The bioassessment for fish, macroinvertebrates and riparian plants could be improved by increasing the sampling effort.

It is necessary to recognise the challenge of making robust conclusions on river condition on the basis of a single investigation such as this. The natural variation in time and space of river health indicators represents an important constraint on river health assessments, especially when they are based on preliminary data sets, or those with limited spatial and temporal resolution. This study made use of historical data available for hydrology, water quality, and social values, and this helped to put the current state of river health into a historical perspective.

Establishing suitable reference values is a particular challenge when first implementing a monitoring program and in the early stages of investigation reference values are likely to include a level of uncertainty. The conclusions on the actual health of the river, and the recommended management responses, need to be read with an understanding of these limitations. Over time, the outcomes of future river health assessments will improve as larger data sets become available, the local aquatic conditions are better understood, and reference values are refined.
Figure 45. Social river health sub-indicator and combined index scores for 2008.

Note: Social river health was calculated for the lower Yellow River in its entirety.

Figure 46. Overall environmental river health scores for the four reaches of the lower Yellow River for 2008.
10.2 Future monitoring research and programs

Further work is needed to refine the method applied during the pilot study to improve the quality of the results, particularly before it can become the basis for a routine monitoring program. It is recommended that the following research topics be considered as part of any future monitoring:

- Confirm initial results and refine the set of recommended indicators by repeating some of the work done in correlating indicator values with levels of catchment disturbance.
- Refine existing water quality guidelines (including development of Chinese standards for TN and TP in the Yellow River) and river health target levels using a load-based approach for indicators such as nutrients and sediments.
- Continue development work on the physical form and social indicator groups.

In addition to the further development of the river health science, a shift towards a routine monitoring program requires significant investment of time and resources to develop the necessary systems and human capacity. A considered approach to these issues is important to ensure the program will be effective and sustainable over the long-term.

The key attributes of an effective and ongoing monitoring and assessment program include:

- the presence of drivers that provide an incentive for governments or other parties to invest in the program and ensure adequate funding is sustained, such as:
  - the requirement for agencies to report on the health of the natural resources they manage
  - the presence of strong public and political support
- generation of useful and easily comprehensible information to all stakeholders (e.g. a report card)
- adoption of a standardised approach to monitoring, evaluation and reporting
- an adaptive management approach embodied within a strategic catchment management plan that requires regular review of progress towards management goals and the consequent revision of management actions to ensure goals are met
- establishment of a sound governance framework to ensure effective strategic planning and implementation as well as providing transparency and accountability.

From the results of the lower Yellow River health assessment pilot study, the following steps are proposed to move to an ongoing monitoring and assessment program:

1. Determine the sampling regime for all chosen indicators, considering both spatial and temporal scales.
2. Investigate the usefulness of alternate indicators of river health that have been trialled elsewhere in China.
3. Develop standard operation procedures in which field and laboratory staff can be trained.
4. Develop a quality assurance/quality control (QA/QC) plan.
5. Prioritise a list of targeted research activities that are designed to improve the science and effectiveness of the program.
6. Consider ways to incorporate the program into existing policy and management frameworks.
7. Consider expanding the program into the upstream catchment and tributaries.

10.3 Management actions to improve river health

The results of the pilot study demonstrate a clear link between human disturbance and river health. Improvements to river health will require a concerted, long-term, and adaptive effort focused on reducing the impacts of both past and present human activities across the catchment.

The preliminary nature of the study makes it difficult to identify specific management responses to address poor river health in the catchment. Based on the pilot study, and other similar studies, it is reasonable to assume that river health will be improved by targeting urban, agricultural and industrial pollution, through improved land management practices to reduce the sediment, nutrient and chemical load entering the waterways. The continued refinement of the environmental flow regime, in accordance with the flow objectives identified in the environmental flows study, would also be expected to improve river health.

The real benefit of a river health assessment system in guiding management actions will only be realised with further monitoring and an improved understanding of the river’s ecosystems. A mature monitoring program may be able to provide more specific information on the state of the river’s health and specific causes of poor health. For example, if knowledge gaps are which pollutants are having the greatest impact on the ecology, and what and where are the sources of these pollutants.
10.4 Application of results to national level policies

Improving river health and, as part of that, monitoring and assessing river condition is a high priority for the Chinese government. In 2011 water management and conservation was, for the first time, the focus of China’s Number 1 Policy Document, a statement issued annually by the State Council that highlights the top policy priorities of the country. China’s Ministry of Environmental Protection is part way through implementation of the National Water Pollution Control and Treatment Program, a 15-year, multi-billion RMB project aimed at improving the health of Chinese rivers. The program includes a major component on river health assessment. At the same time, the Ministry of Water Resources is currently piloting a national river health assessment program and has issued draft guidelines to support this work (NTWGHARL 2010).

The work undertaken during the pilot study provides a number of lessons that should be considered in the development and implementation of these national monitoring programs.

The pilot study was successful in trialling an international method for river health assessment in the lower Yellow River. Establishing appropriate reference values against which indicator values can be assessed is a major challenge. The pilot study set reference values based on a number of different approaches. While these were adequate for the purposes of this study, these indicators and their reference may have little relevance elsewhere, because the lower Yellow River is unique in some respects. China-specific tolerance values are needed, based on local taxonomy and tolerance patterns of individual taxa. Establishing a central repository of ecological data collected as part of river health assessments would provide an excellent basis for developing reference values that are appropriate for Chinese rivers.

Reference values will also vary significantly between different rivers and regions within China. The abundance and composition of different biota in healthy rivers is likely to vary, for example, between upland and lowland streams, between tributaries and trunk streams, and between the wet and dry catchments. Water quality parameters can also show significant natural variation. Reference values therefore need to be established for different river types.

To support this, a river classification should be developed based on landscape and climatic features that are known to influence water quality and biota (such as rainfall, runoff, temperature, geology, topography and other landscape features), but are not directly influenced by human activity. This could be done at a relatively coarse scale initially and refined as the need arises.

The river classification would allow grouping together rivers and catchments that are similar to one another. The selection of indicators and threshold values for indices can then be determined for each class of river. This would include identifying for each river type:

- standards and thresholds for water quality and biological indicators
- aspects of the flow regime that are environmentally significant.

It may be possible to adapt existing classification systems to meet present needs.

A common objective for national governments in developing (national) river health assessment programs is to be able to compare the relative health of different rivers. This allows government to identify priorities for funding of restorative action and to assess the relative success of conservation and restoration activities. This can result in pressure to adopt common indicators and reference values across a country. However, for the reasons discussed above, this is often not a scientifically sound approach because the health of different types of river ecosystems (e.g. from tropical to arid zone environments) may best be assessed using different indicators. It can be argued that it is more important to establish a common reporting framework, by which the results for different indicators from different rivers can be compared against one another. Provided results are scaled in the same way – so that a ‘good’ score or a ‘poor’ score is equivalent – it does not necessarily matter if different indicators or indicator groups are used in calculating river health scores: the scores can still be compared with one another.

In implementing a national river health assessment program, a balance should be struck between avoiding prescriptive guidelines on indicators and reference values, while at the same time ensuring that the methods for data collection and analysis are sufficiently similar to allow results from different rivers and regions to be compared.
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