INTEGRATED RIVER SUSTAINABILITY ASSESSMENT: CASE STUDIES OF THE YELLOW RIVER AND THE GANGES

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A thesis submitted for the degree of

Doctor of Philosophy

Michaelmas Term 2014

To my parents,

for their unconditional love and support.

ABSTRACT

This thesis develops and validates a comprehensive methodology for measuring sustainability of a large river basin by using a tailored indicator set. The concept of river sustainability concerns not only the ecological condition of the river course, but also socioeconomic activities in the river basin. River sustainability is defined from five perspectives: sufficient resource, resilience to water-related risks, access to water supply and other services, productive use of water, and fairness between different users and generations.

The Process Analysis Method (PAM) is employed as the guideline for developing sustainability assessment framework. As a participatory approach, PAM engages stakeholders to identify emerging issues and impacts on sustainability. Through a systematic process, a tailored indicator set is selected and categorized under three domains, namely, environmental performance, social wellbeing, and economic development.

Two case studies have been undertaken, examining the underlying sustainability of the Lower Yellow River basin (LYR) and Upper Ganges River basin (UGR). Extensive fieldwork was carried out in China and India, in order to conduct stakeholder interviews and to collect multivariate data. 18 indicators are selected for LYR and 12 for UGR. The LYR assessment is conducted over the period from 1950 to 2010, whilst UGR features a 10-year period from 2001 to 2010. By processing raw hydrological data and socio-economic statistics, a normalized score is calculated for each indicator in a given year, the value ranging between 0 and 1, where 0 represents poor performance and 1 refers to a fully sustainable status.

The results show that, although social wellbeing and economic status for LYR have progressively improved since 1950, environmental quality declined in the latter half of 20th century, with the lowest point in 1997 when extreme drought occurred. The Yellow River Conservancy Commission (YRCC), the government authority responsible for the LYR, implemented measures to improve the river health by multifunctional infrastructure projects and water allocation regulation. This effort proved to be effective as the general sustainability performance subsequently improved. The UGR study also identifies the trade-off between environmental capital and socioeconomic capital. With vast expansion of hydropower projects and new settlement in flood-prone areas, communities along the UGR are increasingly vulnerable to extreme events. However, the Ganges river basin authority lacks the capacity for integrated planning which would enable projects like flood defence schemes to be undertaken in a proper framework. It is likely that the environmental performance of the UGR will continue to decline, particularly with increasing uncertainty in climate, as the UGR basin management is not improving resilience sufficiently.

By performing this comparative analysis, it has been shown that integrated river basin management should incorporate institutional capacity, stakeholder engagement, resilience and transparency. This research also contributes to underpinning policies for Integrated River Basin Management (IRBM). The assessment provides policy-makers and river managers with a holistic view of the river basin; the framework can be used to track progress towards sustainable development and identify priorities for multi-criteria decision-making.

ACKNOWLEDGEMENT

First and foremost, I would like to express my deepest gratitude to my supervisors, Prof Richard Darton and Prof Alistair Borthwick, for supporting me throughout my DPhil with invaluable inputs, patience and continuous encouragement. I've enormously benefited from their insights into river basin management and sustainability science, and their efforts from structuring the research framework to improving my academic writing. I simply could not wish for more. I'm also grateful to Dr Aidong Yang and Dr Jonathan Chenoweth for taking the time to be my examiners and contributing their insights into my thesis.

This thesis would not have been possible without generous funding from SPORE, the NUS, Peking and Oxford Research Enterprise. Scholarships and travel grants from the Institution of Civil Engineers, BP, Peking University, NUS Environment Research Institute, the Institution of Chemical Engineers, Department of Engineering Science and St Edmund Hall at the University of Oxford are also gratefully acknowledged.

My sincere thanks go to Prof Jinren Ni (Peking University, PKU), for his enormous help with my case study of the Yellow River: providing me with access to multivariate data and supporting my fieldtrip to the Yellow River. I'm very grateful to Prof Wenyi Yao (the Yellow River Institute of Hydraulic Research, YRIHR) for contributing his perspectives of the Yellow River and arranging a road trip to LYR for me, and Mr Simon Spooner (Atkins) for sharing his extensive experiences from EU-China River Basin Management Programme. I would also like to thank Dr Arunabha Ghosh (the Council on Energy, Environment and Water, CEEW), who offered me the opportunity to India and to conduct my case study on the Ganges, and Dr Ravi Chopra (the People Science Institute, PSI), who helped with my research visit to the Upper Ganges. And I'm also very grateful to Prof Fongyau Sam Li (National University of Singapore, NUS), for promoting research collaborations through SPORE and supporting my research visits to NUS.

Special thanks go to Mr Francis Budge (CH2M Hill), who offered me the initial opportunity to move to the UK, and has been mentoring me throughout my environmental consulting career and postgraduate studies at Oxford. I would also like to thank my friends at the China Youth Climate Action Network and the Youthink Centre, who made my attending the UNFCCC Climate Change Conferences and the Rio+20 possible; and all my friends at Oxford for their great company, support and inspiration, who made my DPhil an intellectually stimulating and thoroughly enjoyable experience.

I am obliged to many of my colleagues in China and India who supported my case studies and participated in my stakeholder interviews:
PKU: Dr Tianhong Li, Ms Linlin Liang, Dr Xiaowei Gao, Dr Qian Chen, Dr Xiaolin Mao; YRIHR: Dr Xiaohui Jiang, Ms Xiaoping Li, Mr Shaojun Qu, Mr Yean Zhao, Mr Yan Wu, Prof. Shengli Zhang, Mr Pu Qi, Mrs Liu, Mr Zhengzhou Sheng; CEEW: Dr Nirmalya Choudhury, WWF India: Dr Upali Amarasinghe, Suresh Babu, Yamini Panchaksharam, Mr Rudresh Sugam; PSI: Dr Anita Sharma, Dr Ravi Chopra, Ms Meena Yadav; Ghandi Peace Foundation: Anumpam Mishra; IWMI: Dr Luna Bharati.

I am grateful beyond words to my parents, for everything they have done for me.

ABBREVIATIONS

ACEDP	Australia China Environment Development Partnership
BCM	Billion cubic meters
BOD	Biochemical Oxygen Demand
CEEW	Council on Energy, Environment and Water
CWSI	Canadian Water Sustainability Index
DO	Dissolved Oxygen
ED	Economic Development
EP	Environmental Performance
GDP	Gross Domestic Product
IRBM	Integrated River Basin Management
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
LYR	Lower Yellow River
MDGs	Millennium Development Goals
MWR	Ministry of Water Resources
PAM	Process Analysis Method
PKU	Peking University
PSI	People Science Institute
RBMP	EU-China River Basin Management Programme
SW	Social Wellbeing
UGR	Upper Ganges River
UN	United Nations
WASH	Water, Sanitation and Hygiene
WB	World Bank
WPI	Water Poverty Index
WWAP	World Water Assessment Programme
WWF	World Wild Fund
YRCC	Yellow River Conservancy Commission
YRIHR	Yellow River Institute of Hydraulic Research

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CHAPTER 1. Introduction and Literature Review

1.1 Introduction

In the early 1970s, scientists in many fields expressed concern about the carrying capacity of natural systems bearing in mind the social and economic challenges faced by humanity (Meadows et al., 1972). The concept of sustainable development gained wide acceptance after the Brundtland Report was published by the World Commission on Environment and Development in 1987 (Brundtland et al., 1987). The Brundtland Report provided the most widely quoted definition of sustainable development: 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. This statement illustrates the dilemma inherent in human development between meeting human needs, in particular the essential needs of the World's poor, and the limitations on the environment's ability to cope with the consequences of human activities. The concept of sustainable development recognises the interactions between nature, development, and the meeting of basic human needs. These interactions can be conveniently described in terms of the three pillars of sustainable development, namely, economic development, social development and environmental protection(UNCSD, 2002, Assembly, 2005). Sustainable development envisions a path to a sustainable future in which these interactions are well balanced.

The word sustainability comes from the Latin *sustinere*. According to the Oxford English Dictionary the term 'to sustain' is defined as 'to maintain', 'to support', or 'to endure'. In general, discussion of sustainability involves words such as current, future, historic, improve, maintain, equilibrium and conserve (Foster et al., 2008). In the latter part of the 20th Century, environmental degradation has become one of the most challenging issues faced worldwide. There has been a gradual realization that the global stocks of many natural resources are finite, and the traditional unrestricted development associated with widespread pollution is unsustainable. The term sustainability is often quoted, and various definitions are given as '…the capacity of system to maintain output at a level approximately equal to or greater than its historical average, with the approximation determined by the historical level of variability' (Lynam and Herdt, 1989), '…maximizing the net benefits of economic development, subject to maintaining the services and equality of natural resources over time' (Turner, 1988), and 'the dynamic equilibrium between natural inputs and outputs, modified by external events such as climatic change and natural disasters' (Fresco and Kroonenberg, 1992).

There are two contrasting views of sustainability from the resource-economist's perspective, *strong sustainability* and *weak sustainability*. Based on Solow (1974), Hartwick's rule shows that, the amount of investment in human capital i.e. infrastructure, labour and knowledge stocks, needs to be exactly offset by the stocks of non-renewable resources(Solow, 1974, Hartwick, 1977). Hence, *weak sustainability* is the idea that natural capital can be substituted by human capital, where human capital incorporates resources such as labour, knowledge and institutional capacity whist natural capital covers the stock of environmental assets such as fossil fuels, biodiversity and other ecosystem services (Ayres et al., 2001, Solow, 1986). In the context of weak sustainability, the overall stock of man-made capital and natural capital remains constant over time. On the contrary, strong sustainability suggests that human capital and natural capital, although they complement each other, are not interchangeable. Natural capital differs from other forms of capital because it has unique characteristics; therefore it is inappropriate to duplicate natural capital by humans or human-made capital. Unlike weak sustainability, strong sustainability values ecological scale over economic gains. It implies that nature should be passed on from one generation to the next intact in its original form, uncovering the inter-generational equity concerns.

The criticism of weak sustainability is that, whereas monetary values can be assigned to manufactured goods and capital, it can be very difficult to assign monetary values to natural resources and ecosystems services (Martínez-Alier, 1995). And the concept of weak sustainability does not consider the fact that some natural resources and services are irreplaceable (Wilson, 2010). Nevertheless, social scientists consider the pursuit of strong sustainability unpractical. Sustainability possesses the attribute of a social-ecological system, which emerges through colonization of natural systems. For instance, agricultural activities in primitive times transformed natural ecosystems into farmland whilst in modern times people became dedicated to extending existing cities to periurban spaces. Weisz *et al.* (2001) defined this as “the intended and sustained transformation of natural processes by means of organized social interventions for the purpose of improving their utility for society”. Therefore, the connection between colonization and sustainable development lies in the efforts of changing the dynamics of a natural system in the interests of the human society (Henriques and Richardson, 2004, Narodoslawsky and Krotscheck, 2004).

Elkington (1994) interpreted the concept of sustainability by the Triple Bottom Line (TBL), a traditional term used in accounting (Elkington, 1997). By adding environmental awareness and social wellbeing to corporate profits, the TBL takes account of the responsibilities that a business has: not only to make a financial return on capital employed, but also to consider environmental and social impacts. The TBL is sometimes said to consist of three Ps: People, Planet, Profit. With acceptance and ratification by the UN (2007), TBL derives the three constituent domains of sustainability, namely, environmental sustainability, social sustainability and economic sustainability. Our assessment is based on these three domains of sustainability. TBL is designed as a mechanism through which a company's performance can be assessed, in a way that is consistent with the concept of weak sustainability. *Weak sustainability* envisages exchange between natural capital, social capital and economic capital over time. When making our assessment, we monitor the total capital reserve, which tackles the inter-generational equity issue raised in a strong sustainability context.

1.2 Measuring Sustainability

In the 25 years since the Brundtland Report was published, much effort has been dedicated to applying the concept of sustainable development in practice. Although the big picture of sustainable development was laid out in the Brundtland Report, sustainability remained a vague terminology without specific focuses (Darton, 2005). Quantitative measurements of sustainability are therefore required in order to evaluate to what extent sustainability is being achieved, to track progress towards sustainability, and to provide information and guidelines for development projects

(Kates et al., 2001, Kates et al., 2005). Comprehensive, reliable analysis of sustainability also provides a sensible anticipation of changes (OECD, 2001). As a result, the assessment equips decision-makers with the means to focus on the priorities without losing sight of emerging issues or other components of sustainable development, even if they are not (yet) priorities (Dalal-Clayton and Sadler, 2014). This also provides a robust basis for monitoring and evaluating the effectiveness of a policy, strategy, plan, or initiative, further to adjusting and underpinning it as necessary (Dalal-Clayton and Sadler, 2014, Dalal-Clayton, 2002).

However, the measurement of sustainability is an arduous task in practice. Sustainable development, representing the complex nexus of humans, nature and development, involves the dynamic interaction of massive factors whilst their correlations and causations remain unclear (Dalal-Clayton, 2002). In general, good measurements need to incorporate four elements: transparency, consistency, participation and usefulness for decision-making. Dalal-Clayton (2002) lists the following three basic principles: firstly, setting up clear objectives of the analysis and criteria for prioritizing analysis; secondly, employing an accessible, participatory method to engage both stakeholders and independent experts; and thirdly, developing a consistent system for generating knowledge. Dalal-Clayton also notes that up-to-date information is required for understanding the changing world.

In the past decade, various frameworks and tools have been developed in an effort to obtain integrated measures of sustainability, including indicators, benchmarks, audits, indices, accounting parameters, as well as assessment appraisal and other reporting systems (Bell and Morse, 2008). To understand the nature of sustainability assessment, Ness et al. (2007) divided sustainability measurement into the following categories: indicators and indices; product-related assessment, including material and energy flow assessment and life cycle assessment; and integrated assessment, often used to measure policy implementation. The framework proposed by Ness et al. also employs an overarching category associated with monetary valuation. Though not exhaustive, the framework covers most of the tools that are frequently discussed in literature or used in practice, as seen in Figure 1.1.

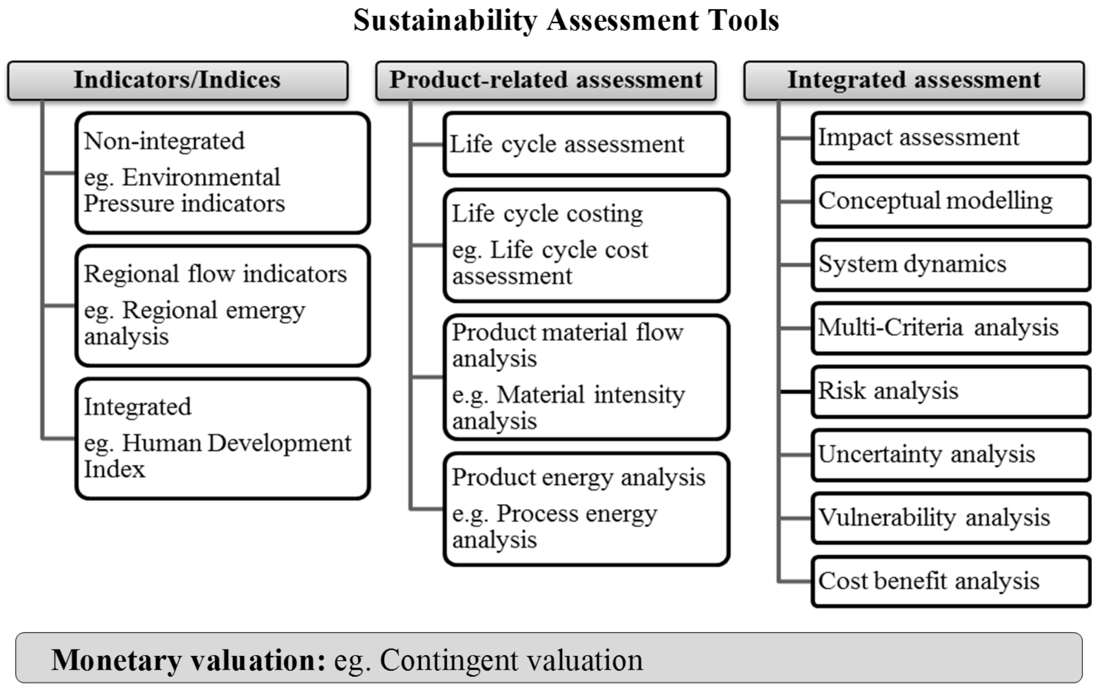


Figure 1.1 Categories for sustainability assessment tools (Ness et al., 2007)

Different measurement systems have their particular advantages and disadvantages. The three main approaches for integrated sustainability assessment include accounts, narrative assessments, and indicator-based assessment. Accounts are commonly used to measure sustainable economic welfare. Based on large quantities of raw data, accounts are converted to a common unit such as money or energy (Dalal-Clayton and Sadler, 2014). This presents a highly consistent and useful approach that covers highly important but detailed aspects of sustainability. Although accounting requires specific knowledge and expertise, participation of stakeholders is limited. Narrative assessments, combining text, maps, graphics and tabular data, are usually very flexible and easy to understand. Such assessments may use indicators, but are not built around them; and the indicators used may change from one report to another. Their strength of narrative assessment is that it is user-friendly and participatory. However, narrative assessment does not involve a systematic, consistent choice of topics. Certain questions are left unanswered: such as, which topics have been omitted, or has a topic been left out because it is unimportant or simply due to data gap?

Indicator-based assessments are potentially more transparent, consistent and useful for decision-making. Yet, whether they fulfil their potential depends on how well they are designed and implemented. Considerable attention is paid to selecting the indicator set systematically. Indicators enable assessments to be selective yet comprehensive. Given that they are selected in a systematic way, indicators are better equipped to cover the wide array of issues which adequately portray human and environmental conditions (Dalal-Clayton and Sadler, 2014). Stakeholders' participation is essential to ensure that the assessment incorporates their values and addresses their concerns. At the same time, those who undertake the assessment must make sure that it is technically sound and withstands scientific scrutiny. Once the measurement tool has been selected carefully to meet specific purposes, indicator-based assessment can be applied to various fields and at different scales (Dalal-Clayton, 2002).

Table 1.1 Comparisons of integrated sustainability assessment approaches

Approach	*Account*	*Narrative assessment*	*Indicator-based assessment*
Transparency	Low	Medium	High
Consistency	High	Low	High
Participation	Low	High	Medium
Usefulness for Decision-making	Medium	Medium	High

(Dalal-Clayton, 2002)

Sustainable development indicators (SDIs) have been used intensively to improve stakeholder engagement and to guide policy-making (Singh et al., 2009, Pintér et al., 2005, Bell and Morse, 2008, Ness et al., 2007). Agenda 21 states that: *indicators of sustainable development need to be developed to provide solid bases for decision-making at all levels and to contribute to the self-regulating sustainability of integrated environmental and development systems* (Robinson, 1993). SDIs play a critical role of communication, and monitor progress towards a goal in a simplified, consistent manner (Hammond et al., 1995, Walmsley, 2002). The indicator set can be interpreted to give metrics which are a collection of carefully chosen measurements that quantify each indicator and cover relevant environmental, economic and human/social impacts. The strength of the SDI set lies in its ability to summarise and focus attention on the essential elements of a complex situation. SDIs are extensively used, for example, in assessing the sustainability of whole countries (UN, 2007, Hall et al., 2010), water resources (Sullivan, 2001, PRI, 2007), companies (GRI, 2006), and manufacturing operations (Tallis et al., 2002). SDIs present a highly efficient tools by which to manage, synthesize and simplify large amounts of multidisciplinary information.

Extensive application of sustainability indicators face two major challenges: increasing complexity and the demand for simplicity (Dalal-Clayton, 2002). The best way to overcome these problems appears to be through combining indicators into composite indices. Such composite indices could provide a clear picture of the entire system, reveal key relationships between the three domains of sustainability and between major subsystems, further facilitate the analysis of critical issues and trends. A composite index is constructed according to a theoretical framework or definition (Nardo et al., 2005). Such an approach allows for the creation and evaluation of multi-dimensional concepts which cannot be represented by a single indicator (Singh et al., 2009, Nardo et al., 2005). Examples, such as the well-known Human Development Index (UNDP, 2006) and the Environment Performance Index (Yale, 2002), demonstrate the strength of composite indices in quantifying complex issues.

The composite index approach, however, introduces elements of uncertainty. Due to the mechanisms used for including or excluding indicators in the index, and the need to decide how to weight and normalise data, composite indicators have been criticised to be subjective(Nardo et al., 2005)a. Moreover, Saisana and Tarantola (2002) have raised concerns that composite indices, 'if poorly constructed or misinterpreted, may invite simplistic policy conclusions or even send misleading messages'. It has therefore been suggested that a combination of uncertainty and sensitivity analyses should be included in order to gauge the robustness of any composite indicator in order to increase transparency and to frame policy-making (Nardo et al., 2005, Singh et al., 2009). Notwithstanding these difficulties, which must be carefully dealt with, composite indicators can prove to be very useful in practice. A well-structured composite index can be used to interpret a large variety of different data while focusing attention on and simplifying the problem (Atkinson et al., 1997), facilitate public communication, and further promote accountability (Saisana and Tarantola, 2002). Methods to calculate composite index will be discussed in section 2.5.3.

1.3 Water Sustainability Assessment

Of the world's natural resources, freshwater is critically important as it sustains the global ecosystem and human civilization. In the latter part of the 20th Century, awareness dawned that global stocks of water resources are finite (Gorre-Dale, 1992). As populations and economies grow, water scarcity and degradation pose a serious and growing threat to socio-economic development and environmental protection. Hence, sustainability of water resources is strategically vital to sustainable development. In this context, the water and development nexus has been highlighted by the work of Falkenmark (1989), Gleick (1996), Rogers (1997, 2008), and others. The importance of water was addressed at the Rio Earth Summit in 1992 and it features in the UN Millennium Development Goals (UNDP, 2000). More recent researches reaffirm the role of water as a fundamental basis of sustainable development. For instance, a group of senior scientists identified freshwater as one out of nine essential planetary systems whose boundaries must be identified and quantified to 'ensure a safe operating space for humanity and to prevent unacceptable environmental change' (Rockström et al., 2009). Recently, Gleick and Palaniappan (2010) introduced the concept of peak water, referring to the limits of water availability. The term peak ecological water is defined as the point beyond which the total environmental externality costs exceed the total value provided by human use of that water. This concept guides us towards using and managing water in a more sustainable manner. In the 6th World Water Forum, the importance of water in enhancing the quality of life and particularly in achieving green economic growth was also addressed (WWC, 2012).

Given that the availability of freshwater is a fundamental prerequisite for sustainable development, this section examines how sustainability indicators can be applied to the assessment of water resources from different perspectives and at different scales. We describe various measurements including two detailed case studies concerning the Water Poverty Index, and the Canadian Water Sustainability Index. These studies range from large-scale water sustainability performance assessment at country- or basin-level, to the sustainability of a community. Associated with these case studies, we will compare different measurements before introducing our sustainability assessment framework for large river basins.

1.3.1 Measurements for Water-related Issues

Many indicators have been developed to assess and monitor water-related vulnerabilities and risks. A widely-used water stress or water scarcity indicator was proposed by Falkenmark in 1989. This simple metric is represented by the total annual runoff available for human use. According to the Falkenmark indicator, a country or region is in the status of ‘water stress’ or ‘water scarcity’ when water supplies fall below 1,700 m^3 or 1,000 m^3 per capita per year respectively (Falkenmark, 1989). Gleick (1996) introduced the term ‘basic water requirements’ to describe water used for four basic human needs: drinking water for survival; water for human hygiene; water for sanitation services; and water for certain household needs such as preparing food. Gleick suggested that 50 litres water per person per day is the minimum required to meet these basic needs, regardless of an individual's economic, social, or political status. Taking fluctuations in water availability and social adaptive capacity into account, Ohlsson (2000) developed a social resources water stress/scarcity index (Ohlsson, 2000). Based on the Falkenmark indicator weighted according to the UNDP Human Development Index, the social resources water stress/scarcity index captures the social impacts of water resources, and is claimed to be more useful than earlier indices (Ohlsson, 2000, Brown and Matlock, 2011).

To promote integrated water resources management, a broad consensus has been reached that water should be treated as a social and economic good (Rogers et al., 1997, Gorre-Dale, 1992). To measure the economic value of water resources, Allen (1993) developed the concept of virtual water to explain how water is embedded in food production and trade (Allan, 1993, Allan, 1998). The virtual water content of a product can be described as the volume of water used through the whole supply chain that leads to an end product. For instance, research into virtual water has found that the production of one kilogram of beef requires 15,000 litres of water (Mekonnen and Hoekstra, 2010). This concept was said to 'help people, especially those who live in semi-arid and arid areas, to understand the value of water, and thus opens the door to more productive water use' (SIWI, 2007). Closely linked to the concept of virtual water, the water footprint is a geographically explicit indicator, concerning not only volumes of water use and pollution, but also location (Hoekstra, 2008). Water footprint is a practical term which can be applied to assessment at different scales. Researches show that the water footprint of the average US citizen is 2840 m^3 per year, 20% of which is imported from outside the US (Mekonnen and Hoekstra, 2011). The average total global water footprint in the period from 1996 to 2005 was 9087 $10^9 m^3$ per year, of which agricultural production contributed 92% (Hoekstra et al., 2012).

These measurements are carefully designed to describe a critical aspect of the water situation, i.e. water stress, water use efficiency. They are simple, straightforward and easy to understand. They are widely used for benchmarking, informing the public and raising general awareness. However, the information provided by the single-dimension measure is very limited. Comprehensive measurements, incorporating different concerns of water, are needed for multi-criteria decision-making. In the following section, we examine two case studies involving the use of indicator sets, which illustrate how sustainability indicators can be applied to integrated assessment of water resources at different scales.

1.3.2 Water Poverty Index

Designed as a holistic measurement tool, the Water Poverty Index (WPI) is a composite index that incorporates quantified estimates of water availability along with socio-economic variables (Sullivan, 2001, Sullivan, 2002, Sullivan et al., 2003, Lawrence et al., 2002). Taking a different approach to a single indicator, WPI encompasses five key water-related components, namely, resources, access, capacity, use, and environment, and aims to be the first index for assessing water poverty the water sector across countries in a holistic way (Lawrence et al., 2002).

WPI is designed to serve the needs of measuring the progress of the Millennium Development Goals (MDG). Freshwater is vital for human development, yet there are presently over 1 billion people lacking access to safe clean water and 2.6 billion people living without adequate sanitation (UNDP, 2006). According to the MDGs, target 7C aims to ‘halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation’ (UNDP, 2000). As a response to this need, the World Water Assessment Programme (WWAP) was launched by UN-Water in 2000, with the aim of reporting the state of global freshwater resources and progress being made towards the relevant Millennium Development Goals.

What distinguishes WPI from earlier water resource assessment tools is its attempt to ‘move away from the conventional, purely deterministic approaches to water assessment, relying primarily on models and large-scale data’ (Sullivan, 2001). WPI aims to provide a simple, transparent, meaningful assessment without compromising the complexity of the issues. With its focus on water-related poverty, WPI examines the extent to which water stress impacts on human populations, especially those which suffer most from inadequate access to water and sanitation. It enables decision-makers at all levels to determine priority needs for interventions in the water sector.

In an effort to raise all major water-poverty related concerns, the development of WPI has involved extensive engagement of stakeholders, academic experts, practitioners, and policy-makers worldwide. The following issues were identified by the stakeholders: measures of access; water quality and variability; water for food and other productive purposes; capacity to manage water; environmental aspects; and questions of spatial scale (Sullivan, 2001, Sullivan, 2002).

Table 1.2 Five key components of WPI

Resources	Physical availability of both surface- and groundwater, taking into account variability and quality as well as the total amount of water.
Access	Access to water for human use, including distance to a safe source, time needed for collection per household and other significant factors. Access also includes water for irrigating crops or industrial uses.
Capacity	Effectiveness of people's ability to manage water. Capacity is interpreted in the sense of income to allow purchase of improved water, and education and health, which interact with income and indicate a capacity to lobby for the manage a water supply
Use	Different uses of water, including domestic, agricultural and industrial.
Environment	Evaluation of the environmental integrity related to water and of ecosystem goods and services from aquatic habitats in the area.

WPI is calculated in a similar way to HDI, and is expressed as

$$WPI = \frac{\sum_{i=1}^{n} w_i X_i}{\sum_{i=1}^{n} w_i} \tag{1.1}$$

where WPI is the value for a particular location, X_i refers to the i-th component of WPI, w_i refers to the weighting applied to component X_i, and $n = 5$ is the number of components. In this equation, the five components discussed above are given a standardized score ranging from 0 to 100, where 0 and 100 refer to the worst and the best water poverty situations respectively.

Indicator development is a complex process, requiring widespread consultation. To verify WPI, pilot studies have been carried out at community scale in South Africa, Tanzania and Sri Lanka (Sullivan et al., 2003). Feedback from the various participants confirmed that the WPI framework was systematic, transparent, and inclusive. According to (Sullivan, 2001), WPI enhances the understanding of complexities inherent in water-poverty issues, and provides a meaningful assessment by integrating physical, socio-economic and environmental aspects. Hence, the WPI framework can be used to identify the community which performs best, or the development of which component could be most beneficial within a community.

Primarily designed for use at community level, the WPI methodology can however be modified and applied at different scales to suit different needs. Further studies have been done to apply WPI at the global-scale, such as the International Water Poverty Index calculated by Lawrence et al. (2002). This index ranks countries, and communities within countries, taking into account both physical and socio-economic factors associated with water scarcity. Figure 1.2 presents a zonation map of WPI obtained for 140 countries in 2002 using five grades ranging from very low to very high, adopted by UNEP (2005). The result of this global WPI analysis illustrates the poverty and hydrology hypothesis proposed by Grey and Sadoff (2007). This hypothesis states that many of the world’s industrialized countries have an ‘“easy” hydrologic legacy’, which refers to relatively low rainfall variability and easily recovered water resources during their period of development; other nations and societies have remained poor, partly because of their ‘“difficult” hydrological legacy’, where water security can hardly be achieved (desert, flood regions etc.) which has limited their development (Grey and Sadoff, 2007). Brown and Lall (2006) presented a similar finding which shows a ‘*statistically significant relationship between greater rainfall variability and lower per capita GDP*’.

These studies demonstrate the strength of WPI in providing rapid and holistic assessment, and the potential of WPI as a powerful tool to guide decision-making. With wider application of the WPI, a standardized framework could be set up for the purpose of benchmarking. To implement WPI at different scales, data availability and data collection in a cost-effective manner remain major challenges. In the long run, data collection for WPI assessment can be linked to provincial and/or national censuses and water monitoring programmes by UN affiliated organisations, for instance the WWAP by UNESCO (Sullivan et al., 2003).

Figure 1.2 WPI zonation map in 2002 (Ahlenius, 2005)

1.3.3 Canadian Water Sustainability Index

Inspired by the Water Poverty Index, the Policy Research Initiative of Canada launched a research programme on water sustainability assessment in 2005. This resulted in the Canadian Water Sustainability Index (CWSI), a composite water index that provides a methodology for assessing the wellbeing of Canadian communities with respect to freshwater resources (PRI, 2007). In developing the CWSI, various issues were identifieded including scope, scale, applicability, relevance, data, and scoring (PRI, 2006). Through comprehensive stakeholder engagement, 15 indicators were identified relating to specific water sustainability concerns. The indicators were then categorised under five policy headings; namely, resource, ecosystem health, infrastructure, human health, and capacity (see Table 1.3).

Table 1.3 The CWSI framework

Component	*Indicator*	*Description*
Resource	Availability	Amount of renewable fresh water available per person
	Supply	Vulnerability of supply due to seasonal variations and/or depletion of ground water resources
	Demand	Level of demand for water use based on water license allocations
Ecosystem Health	Stress	Amount of water removed from the ecosystem
	Quality	Water Quality Index score related to protection of aquatic life
	Fish	Population trends for economically and culturally significant fish species。
Infrastructure	Demand	How long before capacity of water and waste water services will be exceeded due to population growth
	Condition	Physical condition of water mains and sewers as reflected by system losses
	Treatment	Standard of waste water treatment
Human Health	Amount	Amount of potable water accessible per person
	Reliability	Number of service disruption days per person
	Impact	Number of waterborne illness incidences
Capacity	Financial	Financial capacity of the community to manage water resources and respond to local challenges
	Education	Human capacity of the community to manage water resources and address local water issues
	Training	Training level of water and wastewater operators

(PRI, 2006)

A standardized assessment methodology was employed to quantify these indicators, with the final CWSI score simply calculated by averaging indicator scores, without introducing weights or considering uncertainty. By using standardized scores, the CWSI value for a community was limited within the range 0 to 100, with a higher value implying an overall more sustainable status of freshwater resources. CWSI allows both temporal and spatial comparisons, and analysis of water sustainability. CWSI can be applied to observe a community's progress towards water sustainability over a given period of time, or to benchmark the state of water sustainability both within, and among different communities. Case studies to test the effectiveness of the CWSI were undertaken for six communities in Canada. PRI (2006) outlines the following five-stage procedure for applying CWSI at community scale: 1) community selection, 2) data collection, 3) calculation of CWSI, 4) analysis of results, and 5) review. The case studies demonstrate that CWSI is potentially a powerful tool for rapid assessment of water sustainability. The experience in Canada has been that participants can be very receptive to this approach because of the clarity of its objectives and its straightforward application (PRI, 2007, PRI, 2006). However, CWSI requires further verification to confirm its accuracy as a composite index for assessing water sustainability.

Taken overall, composite indices show strength in guiding different aspects of water management, in which single indicators are clearly inadequate (Fekete and Stakhiv, 2014). WPI shows that a well-chosen indicator set can provide a simple but useful guide to complex issues. WPI is designed to describe the concerns of national water poverty, and serves as a very useful and informative assessment tool for policy-makers. CWSI, which aims to provide integrated measurement of water sustainability is flawed. Developed for a country that is rich in water resources, CWSI simply puts together a set of WPI indicators without highlighting local circumstances or addressing important issues. Without a clear guideline, CWSI monitors the general status of water resources over time, rather than capturing the progress towards sustainable management of resources.

Integrated measurements of water issues, such as WPI, give a useful synopsis of variables and improved our understanding of the relationship between the physical status of water resources (environment, resources availability), and its use and associated welfare (access, capacity, use) (McDonnell, 2008). Yet, a few conceptual issues inherent in WPI have been identified (Molle and Mollinga, 2003, Chenoweth, 2008, Feitelson and Chenoweth, 2002, Komnenic et al., 2009, Salameh, 2000). Firstly, the attempt to combine several dimensions of water problems into a single index often results in weak or wrong conclusions, especially with arbitrary weights applied to the sub-indices (Molle and Mollinga, 2003). For instance, odd associations were identified in the international rankings of IWP, i.e. New Zealand stands next to Nicaragua, and USA to Laos (Molle and Mollinga, 2003, Lawrence et al., 2002). This problem is also noted by the authors that "the information is in the components rather than in the final single number"(Sullivan, 2002).

Secondly, a composite index, which tries to link vaguely defined concepts i.e. IWRM with particular management objectives i.e. poverty relief, sometimes fails to provide adequate measures to deal with these concepts (Chenoweth, 2008). For instance, the measurements used by WPI does not assess whether a country can sustainably provide sufficient water to its people at affordable price. Whilst affordability of portable water represents a major concern for poverty reduction purposes. Komnenic et al. (2009) examined the usefulness of WPI by applying WPI to Sava River Basin countries. The finding suggests that WPI cannot differentiate water poverty from economic poverty in this case, therefore provides limited information for underpinning policy to relieve water poverty.

Lastly, Feitelson and Chenoweth (2002) noted that composite indices applied across an entire country with different geographical, socio-economic conditions and sampling regimes, cannot capture the complexity of water issues within a country. A case study of Sri Lanka, showing large water scarcity variation within a country (Amarasinghe et al., 1999), indicates that WPI cannot express the variation of water issues or provides a holistic review.

To overcome this problem, it is broadly recognized that the indicators should be calculated at a local scale, i.e. river basins or a group of administrative units within the same hydrological boundaries, to give more meaningful results (Molle and Mollinga, 2003, Molle, 2009). The Composite River Sustainability Index, consisting of Environmental Performance Index, Social Wellbeing Index and Economic Development Index is designed to tackle these problems, by focusing the attention on water issues at basin level. The usefulness of the assessment lie in the three sub-indices, which tracks performance of different dimensions of river sustainability. It can help improve our understanding of the interactions between the three pillars of sustainability, further be used as a quick diagnosis of existing or emerging problems.

In light of the above, the composite river sustainability assessment framework will be developed based on a comprehensive review of all the sustainability impacts with regard to a river basin. Clearly principles will be adopted to set the scope of the study, to guide indicator selection and to process the analysis. The framework will be designed to capture the complexity of water problems and to provide a holistic review.

1.4 Aims and Objectives

This research aims to develop and validate a comprehensive methodology based on the Process Analysis Method (described in detail in Chapter 2) for measuring sustainability of a large river basin. Two case studies are carried out, the Lower Yellow River Basin (Chapter 3) and the Upper Ganges River Basin (Chapter 4). The methodology is used to guide the assessment process and to develop an integrated sustainability assessment framework through identifying and evaluating a tailored set of sustainability indictors. Main objectives and contributions of this research are as follows,

- To provide a comprehensive working definition of river sustainability;
- To develop and to validate a river sustainability assessment framework by using the Process Analysis Method as an integrated, transparent and participatory tool;
- To perform a multivariate analysis to examine the underlying sustainability of the Lower Yellow River basin and Upper Ganges River basin;
- To identify major sustainability impact generators for a river basin and to perform a comparative analysis of the two river basins under study;
- To address key elements for IWRM towards sustainable development, and to conclude with policy recommendations.

CHAPTER 2. River Sustainability Assessment Framework

2.1 Sustainability Assessment Principles

The key decision inherent in sustainability assessment by using indicators is the choice of exactly which indicators to include in a set, and which to omit. This process of selection needs to be both transparent, and to follow a methodology designed to produce an indicator set for a particular purpose (Dalal-Clayton, 2002). A framework is a conceptual model that helps develop goals and indicators. It is therefore needed to represent the essential elements of sustainability in the field, and to help develop indicators in a transparent, consistent manner (Darton, 2005). Without a framework, indicators can be nothing more than a conglomeration of disparate data (Becker, 2005). The framework results not just in a set of indicators, it also sets up the criteria for indicator selection and guides the decision-making process. By including a definition and vision of sustainability, the framework provides potential for emerging challenges to be identified (Becker, 2004). Through identifying new indicators, the framework can keep the assessment updated in the context of a changing environment. In this way, it enables paths to continued assessment and provides solid information for policy improvement.

Initiated by the International Institute for Sustainable Development (IISD), the Bellagio Principles for sustainable development assessment were developed in 1996 by a group of experts at the Rockefeller Foundation Centre in Bellagio, Italy (Hardi and Zdan, 1997). Through a comprehensive review of progress to date, the Bellagio Principles summarize the crucial elements for making sustainable development evaluations work (Becker, 2004), further provide step-by-step strategies to construct a holistic sustainability assessment framework (Hardi and Zdan, 1997). Applying Bellagio Principles to case studies, it serves as guidelines for the whole of the assessment process including the choice and design of indicators, their interpretation and communication of the result. The Bellagio Sustainability Assessment and Measurement Principles (STAMP) were devised through a similar expert group process, based on the original Principles as a starting point (Pintér et al., 2012). Intended to be used as a complete set, Bellagio STAMP include 10 principles, which deal with different aspects of assessing progress toward sustainable development, as shown in Table 2.1.

Principle 1 establishes a vision of sustainable development and clear goals that provide a practical definition of that vision in terms meaningful to the decision-making unit in question. Principles 2 through 5 deal with the content of any assessment and the need to merge a sense of the overall system with a practical focus on current priority issues. Principles 6 through 8 deal with key issues of on-going assessment which needs to be accessible, communicative and participatory. Principles 9 and 10 deal with the necessity for establishing a continuing capacity for assessment. With a clearly holistic vision for sustainability assessment, the Bellagio STAMP set up the general practical guidelines for delivering assessment. The Bellagio STAMP are followed in our research on river sustainability, with The Process Analysis Method (PAM) employed for our sustainability assessment follows the Bellagio Principles, with principles reflected at different stages of the assessment. This will be discussed in detail in section 2.4.

Table 2.1 Summary of Bellagio STAMPs (Pintér et al., 2012)

1. *Guiding Vision and Goals*
Assessment of progress toward sustainable development should be guided by a clear vision of sustainability and goals that define that vision.
2. *Holistic Perspective*
Include review of the whole system as well as its parts; consider the well-being of social, ecological and economic system; and consider both positive and negative consequences of human activities .
3. *Essential Elements*
Three pillars of sustainable development must be considered: ecological condition on which life depends; social well-being, consider equity and disparity within the current generation; and economic development.
4. *Adequate Scope* Adopt a time horizon long enough to capture both human and ecosystem time scales thus responding to needs of future generations as well as those current to short term decision-making. Define the space of study large enough to include not only local but long-distance impact on people and ecosystem.
5. *Practical Focus* An explicit set of categories or an organizing framework that links vision and goals to indicators and assessment criteria; A limited number of key issues for analysis; A limited number of indicators or indicator combinations to provide a clearer signal of progress; Standardizing measurement wherever possible to permit comparison; Comparing indicator values to targets, reference values, ranges, thresholds, or direction of trends, as appropriate.
6. *Openness* Make the methods and data that are used accessible to all and make explicit all judgments, assumptions, and uncertainties in data and interpretations.
7. *Effective Communication* Address the needs of the audience and set of users. Draw from indicators or other tools that engage decision-makers. Aim for simplicity in structure and use of clear and plain language.
8. *Broad Participation* Obtain broad representation of different group of stakeholders, which ensures recognition of diverse and changing values. Ensure the participation of decision-makers to secure a firm link to adopted policies and resulting action.
9. *On-going Assessment* Develop a capacity for repeated measurement to determine trends.

10. Institutional Capacity
Assure continuity of assessment by clearly assigning responsibility and providing on-going support, i.e. data collection, documentation, knowledge transfer and technical support.

Endorsed by IISD and other international organizations (i.e. OECD and UNEP), Bellagio Principles have been applied to a series of case studies to facilitate its use and adoption, including Costa Rica's National Development Strategy, United Nations Environmental Program's First Global Environment Outlook, The European Pressure Indices Project, just to name a few (Hardi and Zdan, 1997). It has also been applied to measure sustainability of water resources. For instance, the Bellagio Principles was adapted to guide sustainability assessment of Israel's water system (Kay, 2000). Although the Principles were not applied to single indicators, i.e. Falkenmark Water Scarcity Indicator developed in the 1980s, the widely quoted composite index, Water Poverty Index, reflect some of the Principles (Sullivan, 2002). In our research, the Bellagio Principles (and STAMP) is considered as a holistic guidelines for constructing sustainability assessment framework, and is followed in our entire assessment process.

2.2 Framework for Indicator Selection

Moving on to the selection of indicators, the Pressure-State-Response framework (PSR) was developed by OECD (1994) based on Rapport and Friend's state-response model for analysing environmental statistics (Rapport and Friend, 1979). PSR examines the interactions among environmental pressures, the environmental status and system responses (OECD, 1994), and is commonly used for developing interdisciplinary indicator sets and structuring integrated assessment. A more comprehensive framework, the Driving Force-Pressure-State-Impact-Response (DPSIR), was extended from PSR by the European Environmental Agency (EEA) for reporting air pollution caused by transport and industry in the European countries. It is used for reporting impacts of transport and infrastructure on the environment. The core of DPSIR is to examine the cause and effect relationships of human activities and the environment.

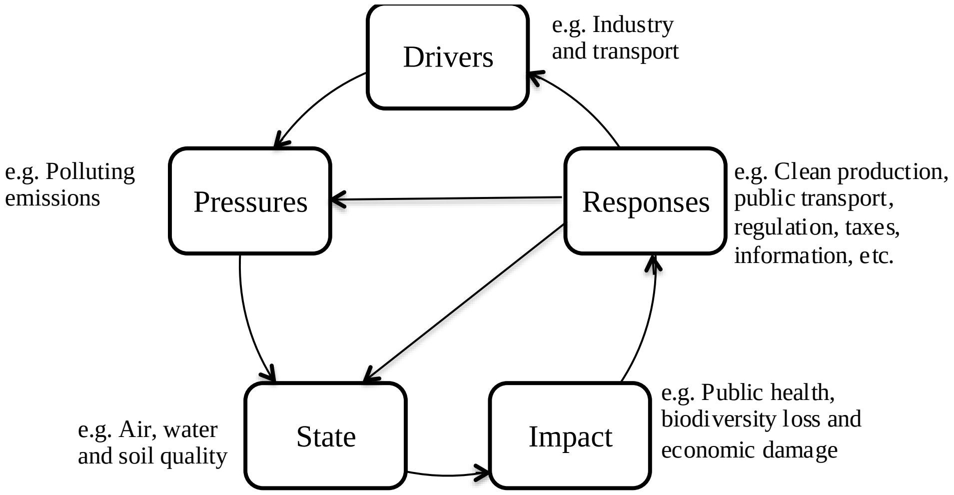


Figure 2.1 DPSIR framework

Figure 2.1 explains the DPSIR framework in terms of a conceptual model. *Driving forces*, such as industrial development and transport, introduce *Pressures* on the environment, such as excessive consumption of natural resources and harmful emissions, which then degrade the environment and generate *Impacts* on human health and eco-systems. This leads human society to *Respond* with various solutions such as regulations and policy tools. Since late 1990s, the DPSIR has been extensively used to analyse environmental issues, ranging from global environmental outlook (Mnatsakanian, 2002), national performance of water resources by the World

Water Assessment Programme (U.N.Water, 2009), and ecological status of localized watersheds under the European Water Framework Directive (Borja et al., 2006). The DPSIR framework has also been extended from environmental reporting to the evaluation of sustainable development by international organizations.

However, the DPSIR has been criticized for several shortcomings either inherent in its concept or emerging from its applications. Theoretically, the DPSIR focuses on human activities as the driving forces, ignoring non-human drivers i.e. natural variables and uncertainty in this framework (Bowen and Riley, 2003, Berger and Hodge, 1998). Without considering the dynamics of the system, the framework is unable to handle the cause-consequence relationship, suggesting linear unidirectional causal chains. DPSIR fails to identify the impact of aggregated, informal responses to the drivers and pressures related to sustainability challenges (Carr et al., 2007). It is argued that DPSIR cannot examine the complex relationship of human beings and natural resources (Berger and Hodge, 1998, Rekolainen et al., 2003). Practical issues have also been identified in recent applications of the DPSIR framework. An expert-driven, evidence-focussed mode of using DPSIR is giving way to the use of the framework as a heuristic device to facilitate stakeholder participation, and communication between different stakeholders (Atkins et al., 2011).

From a social constructivist perspective, the DPSIR framework lacks the capability to deal with multiple attitudes. As it tends to reproduce the particular discursive positions of the analysts, the framework is incapable of generating neutral knowledge (Svarstad et al., 2008). Therefore it is difficult for DPSIR to establish a holistic framework for indicator selection, nor facilitate good communications between researchers, and stakeholders and policy makers.

System dynamics is a model-based framework to understand the interactions within a complex system. Although similar to DPSIR, in focusing on the cause and effect relationship of different factors, SDM aims to quantify that relationship through identifying system variables affecting the dynamic equilibrium (Giampietro and Mayumi, 1997). An early example of SDM was captured in the book *the Limits to Growth* (Meadows et al., 1972). Based on a computational model of exponential economic and population growth with finite resource supplies, the model aimed to explain how exponential growth interacts with finite resources, rather than making specific predictions. Five variables, including world population, industrialization, population, food production and resource depletion were examined under three scenarios. The first two scenarios showed the world would overshoot and collapse in the latter part of the 21st century, while the third scenario led to a stabilized world (Meadows et al., 2004). The work raised much attention regarding resource depletion in the 1970s, and has resulted in fierce debates among scientists, politicians and economists over the past 40 years (Bardi, 2011). After comparing *the Limits to Growth* with the reality, a general consensus has been reached that '*the changes in population, industrial production and food production are all in line with the predicted socioeconomic collapse in the late 21st century*' (Turner, 2008), and '*the conclusions are still surprisingly valid*'(Nørgård et al., 2010).

Since the late 1990s, SDM has been extended to deal with the complex nature of sustainability assessment. The strength of SDM lies in its quantification of the equilibrium between demand and supply, and so SDM is often used in the fields of land use simulation (Le et al., 2010), supply chain analysis (Sarimveis et al., 2008), transport study(Powell et al., 1998) and more extensively in power system and energy efficiency assessment (Karlsson and Hill, 1994, Dagdougui et al., 2010). SDM aims to build comprehensive mathematical models to simulate the cause-consequence relationship involving many interacting factors within the system. When scaled up, large quantities of data are required to set up the framework, whilst it remains very difficult to specify the dynamics accurately. It is argued (Baron et al., 2002) that SDM is useful for understanding the interactions and the trends through general simulation, but incapable of providing objective, precise information concerning complex systems, especially human interactions. Nevertheless, there has been criticism of the weak data used in the modelling process (Solow, 1973), and the neglect of behaviour change and technology innovation (Schmandt, 2010).

In the present research, the Process Analysis Method is employed to guide indicator selection (PAM). The PAM was originally developed by Chee Tahir and Darton (2010), to measure sustainability of business operations. Serving as a guideline, the PAM presents a systematic approach for structuring the assessment, in terms of identifying the perspectives of sustainability and selecting indicators. Similar to DPSIR and SDM, the core of the PAM methodology is the idea of *cause and effect*. Impacts on sustainability are identified. The impact generators are termed as internal impact generators (IIGs) and external impact generators (EIGs) in this research, where internal refers to within the system, external means beyond the system boundary. These generators produce effects/impacts on the capital stored in three domains of sustainability, namely, the environmental, social and economic domains. And these changes/consequences are described by the indicators, and measured by carefully chosen metrics.

Table 2.2 compares the three framework discussed above. What differentiates PAM from DPSIR and SDM is that PAM does not require modelling of the system. PAM focuses on the impact generators and the impacts on sustainability, not the interacting dynamic of *cause and effect*. Compared to the software testing theory, the three frameworks described earlier can be considered as black box, grey box and white box. The method of testing without having any knowledge of the interior workings of the application is called Black Box testing. White box is the opposite, whereby detailed investigation of internal logic is required. Grey Box is a way to test the application with limited knowledge of the internal workings of an application. In the present research, PAM, the black box approach, is the preferred framework because of its flexible, transparent and participatory nature. The implementation of PAM has well followed the Bellagio STAMPs: it considers the three pillars of sustainability and covers an adequate scope; it focuses attention on key issues and allows stakeholders' participation; furthermore, it has the capacity for on-going assessment and determining the trends towards sustainable development.

Table 2.2 Comparison of DPSIR, SDM and PAM

Framework	*DPSIR*	*SDM*	*PAM*
What the framework measures?	Cause and effects	Cause and effects, and interactions	Effects/impacts only
Participatory	High	Low	High
Flexibility	Low	Low	High
Systematic	Medium	Medium	High
Communicative	Medium	Medium	High
Uncertainty	Medium	High	Medium
Sensitivity	Medium	High	Low
Risk of double counting	High	Medium	Low

Comparing to DPSIR, PAM focuses on the impact generators, and all the indicators are selected to describe the impacts. In this way, it minimises the issue of double counting which DPSIR may have, and simplifies the indicator set. SDM models are built on series of assumptions, which introduces the issues with uncertainties and may skew the assessment results. PAM, on the other hand, provides an overall understanding of a large complex system through intensive literature review and stakeholder engagement. It measures specific sustainability concerns (i.e. sufficiency, equity) identified through the process. With clearly objectives, PAM demonstrates the strength in providing simplified yet meaningful results.

2.3 Working Definition of River Sustainability

Of the World's natural resources, freshwater is critically important as it sustains the global ecosystem and human civilization. In the latter part of the 20th Century, awareness dawned that global stocks of water resources are finite (Gorre-Dale, 1992). As populations and economies expand, water scarcity and degradation pose increasingly serious and growing threats to socio-economic development and environmental protection. Hence, sustainability of water resources is strategically vital to sustainable development. The concept of river health evolved from scientific principles and changing societal values concerning integrated river basin management (Boulton, 1999, Karr, 1999, Norris and Thoms, 1999, Norris and Hawkins, 2000). The maintenance and restoration of 'healthy' river systems have become important objectives of environment and water resources management (Rapport et al., 1998, Li, 2005). Table 2.3 illustrates the evolution from environmental impact assessment to sustainability appraisal. In the context of river basin management, river health studies have helped focus interest on the concept of river sustainability, while also providing a foundation for assessing river basin sustainability.

Table 2.3 The evolving paradigm from EIA to SA (Sadler, 1999)

Paradigm/level/stage	Key characteristics
First generation Project-level Environmental Impact Assessment (EIA)	Includes social, health and other impacts, cumulative effects and biodiversity
Second generation Strategic Environmental assessment	Applies to policy, plans, programmes and legislation
Third generation Environmental Sustainability Assurance	Use EIA and SEA to safeguard critical resources and ecological functions and offer residual damage, plus environmental accounting and auditing of natural capital loss and change
Next generation Sustainability Appraisal (SA) and Integrated Environmental Management	Integrated or full cost assessment of the economic, environmental and social impacts of proposals. Comprehensive or full cycle assessment and control of all impacts of existing and proposed actions.

Distinct from river health, river sustainability comprises not only the natural value of the river course from an ecological perspective, but also the social development and economic activity in the river basin. River sustainability depends on whether the river system can support the long-term ecological, economic, and social functions of the river basin as a whole. A broad definition is therefore required of river sustainability in keeping with the principles of sustainability, which should be backed up by quantitative measurements. Based on the Brundtland Report, river sustainability can be interpreted as,

> *The development of water resources in the river basin to meet the needs of the present generation without compromising the ability of future generations to meet their own needs.*

Through an extensive review of literatures (see section 1.1 and section 1,2) and case studies on river basin management (see section 3.1 and section 4.1), we summarises the five elements of a robust framework for measuring river sustainability, as listed below:

Sufficiency

The river system should have sufficient runoff of required quality to maintain the ecological health of the river; while the river should also be able to provide sufficient water resources of required quality to support social settlements and economic activities within the river basin.

Resilience

Resilience is a measure of the ability of a system to absorb changes and still persist (Becker, 2005). In ecological terms, the degree of resilience determines whether the system's functions remain unaffected, or decrease either temporarily or permanently (Conway and Barbier, 1990). The river system should have the capacity to respond to a perturbation (i.e. excessive discharge) or disturbance (i.e. water contamination) by resisting damage and recovering quickly. The vulnerability of communities to changing circumstances (e.g. climate, deforestation, infrastructure development) should not increase with time.

Access

Communities should have adequate access to the services provided by the river, such as water supply (including safe drinking water) and sanitation, recreation and transportation in order to meet essential requirements for ensuring the wellbeing of communities.

Productivity

The term ‘water productivity’ is similar to the terms ‘labour productivity’ or ‘land productivity’, but now production is divided by the water input. The water resources should be used in a productive and efficient manner to provide socioeconomic development. Water productivity could be measured either in physical output per unit of water, or monetary output per unit of water.

Equity

Equity inherent in sustainability has two aspects, intra-generational equity and intergenerational equity. Intra-generational equity refers to benefits and dis-benefits, which arise from human use of the river system and should be fairly distributed among the various stakeholders. Intra-generational equity reveals the potential conflicts between current and future generations. Renewable water resources in the river system should not diminish with time. Water quality and ecological conditions of the river system should be maintained within safe operating boundaries (Rockström et al., 2009).

2.4 Sustainability Assessment Framework

Deployment of PAM for river sustainability assessment involves five steps. The assessment starts with an in-depth review of the river system. The second step involves defining the term ‘river sustainability’, by addressing interests from stakeholders' perspective. By interpreting sustainability in the context of river basin management, the assessment is structured to meet specific goals, thus meeting the needs of special interest groups. The next step is the core of the assessment: setting up the assessment by selecting and analysing a set of sustainability indicators. The indicators are chosen following the PAM to describe the effects of IIGs and EIGs on sustainability capital. Finally, the indicators and assessment framework is verified through reviewing and stakeholder consultation.

Step 1. Overview of the river system

The assessment starts with an in-depth review of the river functions (Figure 2.2), and interconnections between river health and the social-economic state of the catchment. This reflects Principle 2 (holistic perspective) and Principle 3 (essential elements) of the Bellagio STAMPs.

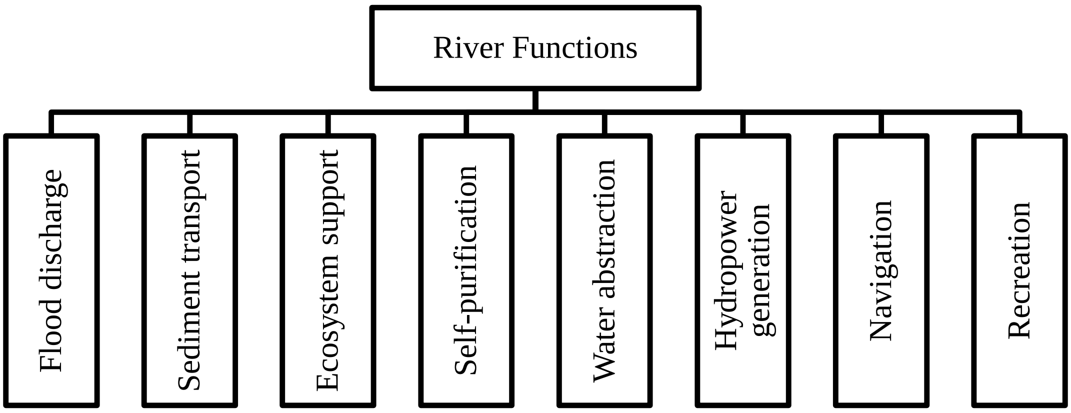


Figure 2.2 Major river functions (Foster et al., 2008)

Step 2. Defining river sustainability

PAM requires selection of an appropriate definition of the term sustainability. Regarding river sustainability, three perspectives have been identified as sufficiency, efficiency and fairness. In our research, the working definition of river sustainability (given in Section 2.3) is used to guide the assessment process. This step reflect Principle 1 (guiding vision and goals) and Principle 5 (practical focus) of Bellagio STAMPs.

Step 3. Set up system boundary

The system boundary is determined by two factors: the spatial and temporal scales (Bell and Morse, 2008). Setting the system boundary is very important as it limits the processes to be included in the sustainability framework (Chee Tahir and Darton, 2010). The spatial scale refers the physical size of the system. In the context of the present research, the river basin is composed of the following features: the entire geographical area drained by a river and its tributaries, and all its inhabitants and users of the associated river system. This temporal scale is set broad enough to cover both intra-generational and inter-generational effects. This links to the Principle 4, adequate scope, of the Bellagio STAMPs.

Step 4: Sep up Sustainability Assessment Framework

PAM considers the impact of the river system on the capital residing in the environmental, social and economic domains. By reviewing the system, activities that have impacts on river sustainability are identified. They are known as impact generators. Internal impact generators (IIGs) refer to activities within the river basin, whilst generators beyond the system boundary, such as global climate change, are the external impact generators (EIGs). Both IIGs and EIGs affect the store of sustainability value, in terms of environmental capital, social capital and economic capital. The consequences are described by sustainability indicators. Measurements for the indicators are consequently identified. Figure 4 illustrates the process by which impact generators affect the capital stores, of the three domains, and how the consequent issues are described by indicators. Finally, receptors of the impacts are named as external impact receivers (EIRs). Step 4 of PAM, the process of setting up the assessment framework, reflects Principle 6 to 8 of the Bellagio STAMPs, which suggest the process needs to be openness/transparent, and effective communication and broad participation should be encouraged.

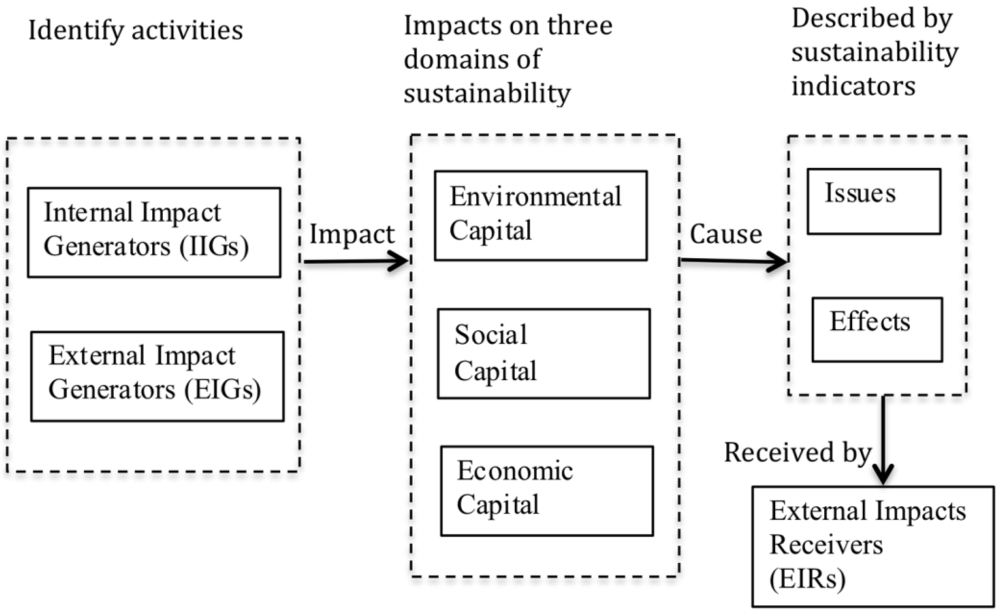


Figure 2.3 PAM sustainability assessment framework

Step 5: Verification

The final step is to verify the analysis and conclusions obtained by applying the sustainability assessment framework. Having selected the indicators, relevant measurements for each indicator need to be carefully chosen and verified. Stakeholders are provided with the preliminary set of indicators as well as measurements to review. General questions for the stakeholders include whether the indicator set is holistic, whether any sustainability concerns have been omitted, whether additional indicators should be included, and whether any indicator appears to be poorly chosen. In cases where measurements are not available due to data scarcity and falsification, surrogate indicators need to be identified where possible.

The rest of the Bellagio Principles are also reflected in PAM, as PAM promotes continuous assessment (Principle 9) and institutional capacity building through stakeholder engagement (Principle 10).

2.5 Data Collection and Analysis

2.5.1 Data Collection

There are two main approaches for collecting data for our case studies: comprehensive review of literature, and field trip. The literature review involves considering not only peer-reviewed journal papers, but also extensive authoritative reports published by ministries (i.e. Minister of Water Resources), government agencies, research institutes (i.e. Institute of Hydraulic Research of the Yellow River), international organizations (i.e. WWF, IWMI International Water Management Institute), and databases from relevant river management authorities (i.e. YRCC, the Yellow River Conservancy Commission). The literature search also helps identify key issues and emerging challenges, and contributes to planning field trips. Extensive fieldwork has been carried out during the present research, including two visits to China and one to India. During the fieldtrips, extensive stakeholder consultation were conducted. PAM uses observations collected from site visits, as well as information collected from stakeholder interviews to identify sustainability concerns, impact generators, and to structure the assessment framework. The field trips also helped gain access to authoritative databases, latest reports and publications. Details of the fieldwork will be discussed in case studies, Chapters 3 and 4.

2.5.2 Normalization Methods

During data processing, normalization methods are used to derive a notionally common scale of relative measurements. Normalization produces meaningful information by transforming indicators into dimensionless numbers on comparable scales. In the present study, each indicator is normalized to a score between 0 and 1, where 0 means unsustainable while 1 means sustainable. There are multiple normalization techniques; commonly-applied methods are listed below.

Standardization (z-scales)

Standardization converts all indicators to a common scale with an average of zero and standard deviation of one, using the normalization formula

$$I_i = \frac{x_i - \mu}{\sigma} \tag{2.1}$$

where I_i is the normalized value for the i^{th} indicator, x_i is the raw value for the i^{th} indicator, and μ and σ are the mean and standard deviation of the non-normalized data set for the i^{th} indicator respectively.

Rescaling (Min-Max)

Rescaling transforms the original data set on the basis of range rather than standard deviation, using the following formula

$$I_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{2.2}$$

where I_i is the normalized value for the i^{th} indicator, x_i is the raw value for the i^{th} indicator data, $x_{min}$and x_{max} are the minima and maxima across data set *x*. I_i lies in [0,1], with $I_\text{i} = 0$ when $x_i = \min(x_i)$, and $I_i = 1$ when $x_i = \max(x_i)$.

Logarithmic transformation

Logarithmic transformation presents a way to rescale data that is either increasing or decreasing in a multiplicative manner that it does increase (or decrease) linearly. A logarithmic transformation is generally used for handling positively valued data.

$$I_i = \frac{log_{10}\left(x_i + 1\right)}{log_{10}\left(x_{max} + 1\right)} \tag{2.3}$$

where I_i is the normalized value for the i^{th} indicator, x_i is the raw value for the i^{th} indicator data, x_{max} is the maximum across data set *x*. $I_\text{i} = 0$ when $x_i = 0$, and $I_i = 1$ when $x_i = x_{max}$.

Square transformation

Square and square root transformation methods are sometimes applied to data in the form of percentages. This provides a method to rescale the data distribution according to the needs. Square transformation is calculated using the following formula,

$$I_i = x_i^2 \tag{2.4}$$

where I_i is the normalized value for the i^{th} indicator, x_i is the raw value (in percentage) for the i^{th} indicator data.

Square root transformation

This transformation of data is sometimes used for percentages, such that

$$I_i = \sqrt{x_i} \tag{2.5}$$

where I_i is the normalized value for the i^{th} indicator, x_i is the raw value (in percentage) for the i^{th} indicator data.

Normalization provides standardized scores and enables comparison, however, one disadvantage is that regardless of the scales of variation, Ii values are discretized with the same distribution (0, 1). This introduces the risk of misleading results. For example, if there is little variation in the data due to good performance, there will be at least one year where $I_i = 0$, suggesting unsustainable, which in fact is not the case (Foster et al., 2008). To tackle this problem, sustainability benchmarks are set referring to literature or stakeholder's comments for some indicators (see River Channel Capacity Indicator in 3.3.3).

Another issue with normalization is that, some socio-economic indicators give a score of 1, suggesting sustainable in the most recent year (also known as the "best" year). In view of a continuous assessment, the score for that year may drop significantly due to continuous growth of economy or social wellbeing so that the "best" case changes (see indicators in section 3.5 and 4.5). In light of this limitation, we argue that the assessment aims to measure whether the river basin can meet the current needs. The "best" year may change in a continuous assessment, yet, the assessment provides up-to-date information on sustainability performance, also enables vertical comparison.

CHAPTER 3. Yellow River Sustainability Assessment

3.1 Background

3.1.1 River Profile

The Yellow River is the second-longest river in China after the Yangtze and the sixth-longest in the world. Rising in the Yueguzonglie Basin 4,500 m above sea level in the northern side of Bayankala Mountains, the Yellow River loops north, bends south, then flows eastwards for 5,464 km until it empties into the Bohai Sea (as shown in Figure 3.1). The Yellow River can be divided into three stages: the upper reaches, the middle reaches, and the lower Yellow River. Approximately 90% of the runoff enters the upper reaches of the Yellow River, which runs through mountainous and arid regions for 3,472 km and ends at Hekouzhen in Inner Mongolia just before it sharply turns to the south. The middle reaches of the river, passing through the Loess Plateau, extend from Hengkouzhen to Huayuankou. The Loess Plateau is a rapidly eroding basin consisting largely of thick deposits of aeolian loess. Sediment from the Loess Plateau accounts for 90% of the silt discharged to the river. The Lower Yellow River (LYR) traverses a course of 786 km from Huayuankou to the Bohai Sea, near Lijin in Shandong Province. Due to accumulation of sediment, the LYR is known as a 'suspended river', which has a riverbed with an average of 5m higher than the surrounding ground beyond both banks. In the most extreme cases, the river bed of the LYR is 20 m higher than the ground of Xinxiang city, and 13m higher than Kaifeng city, each of which has a population of 5 million people. The Lower Yellow River also features a narrow basin, which accounts for only 4% of the total basin area, and a frequent changing river course due to silt-up of main channel.

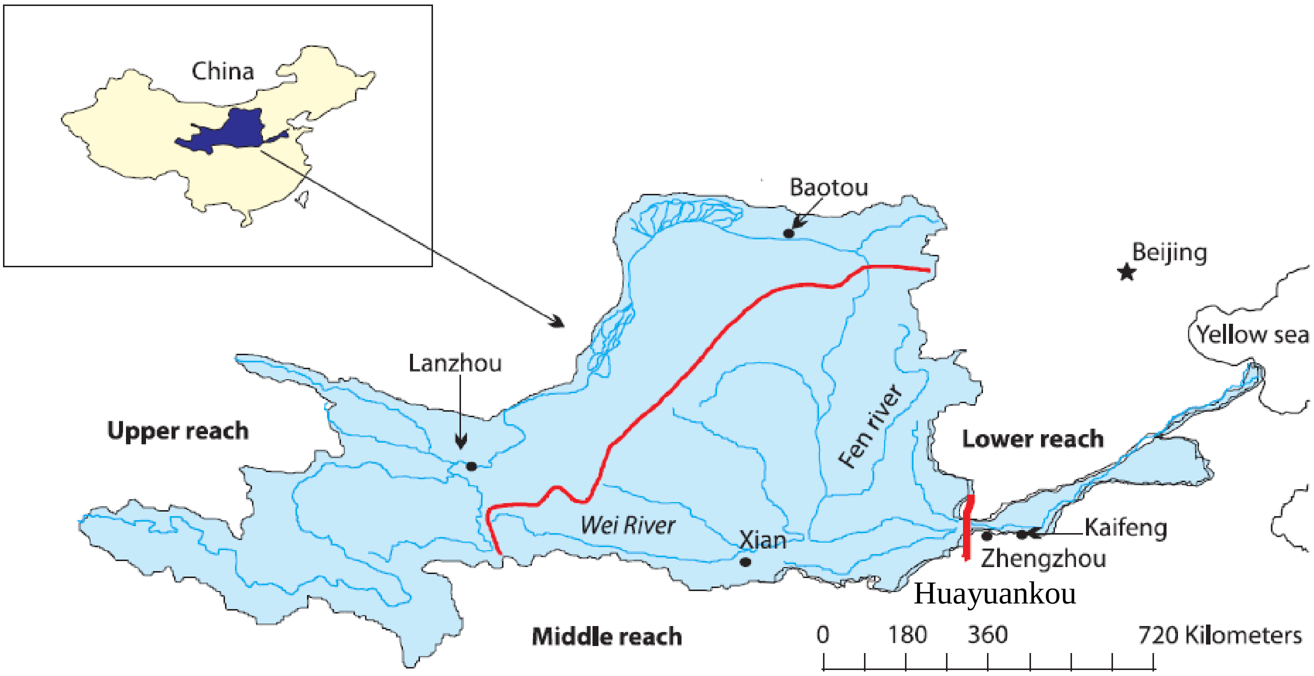


Figure 3.1 Map of the Yellow River basin

Situated in the middle and northern part of China, the Yellow River basin is of temperate continental climate, as it is humid in the southeast, semi-arid in the central area, and arid in the northwest. The coldest days occur in January and the hottest in July, with temperatures annually range from 20 to 30°C. Most of the Yellow River basin is located in a monsoon climatic region where rainfall is affected greatly by monsoon and to a certain degree by regional terrain features. The average precipitation of the whole river basin is 500 mm every year, but varies significantly over space and time (Gippel et al., 2011).

The Yellow River is famous for its excessive sediment. As the world's most heavily silt-laden river, the Yellow River got its name from the perennial ochre-yellow colour of the water. The average annual runoff of the Yellow River is 58 billion m^3 and the average annual sediment transported in the Yellow River is approximately 1.6 billion tons (Li, 2009). This makes the average annual sediment concentration as high as

35kg/m^3, which is unique compared to other river courses in the world (Chen, 1998). The maximum sediment concentration as recorded at Xiaolangdi gauging station in 1997 is as high as 941 kg/m^3. Both the average sediment concentration and the total annual sediment load of the Yellow River are the highest in the world. Table 3.1 compares the water and sediment features of the Yellow River to other world famous rivers. For instance, the Ganges of India carries the second largest sediment load, corresponding to an average of 1.45 billion tons of sediment annually. But its annual runoff, 371 billion m^3, is more than 6 times that of the Yellow River. The Colorado River of America, another famous silt-laden river, has a very high level of sediment concentration of 27.5kg/m^3. However its annual sediment load is only 135 million tons, less than 10% of the Yellow River’s (Li, 2009). Further, the Yellow River is also marked by an uneven distribution of water and sediment throughout the year. A few big storms during the flood season contribute approximately 60% of the runoff together with 80% of the sediment (Li, 2005).

Table 3.1 Water and sediment features of major world rivers (U.N.Water, 2009)

River	Runoff (10^9 m3)	Sediment Concentration (kg/m3)	Population (million)
Yellow River	58	35	110
Yangtze River	951	0.123	400
Ganges River	394.2	3.9	400
Colorado River	19.4	27.5	50
Nile River	89.2	1.79	65
Mississippi River	529.5	0.274	60.2

The Yellow River is also known as the cradle of Chinese civilization. The earliest human settlements found in the Yellow River basin date back to the 1 million years ago. The basin is the birthplace of ancient Chinese civilizations and the most prosperous region in early Chinese history. The Han Chinese, comprising 98% of China's population, claim to be descendants of the *Yan Huang Emperor* (2697 to 2597 BC), who variously resided along the middle and lower reaches of the river. The most famous and influential Chinese philosophers, Confucius (551 to 479 BC) and Mencius (372 to 289 BC), were also born and lived in the Yellow River basin. Nowadays, the river drains a basin of 795,000 km^2, which is home to 110 million people, approximately 9% of China's population. As the main water source of Northwest and North China, the Yellow River, accounts for 2.2% of the total runoff of all rivers in China, but supports 12% of the nation's population and shoulders the water-supplying duty of 15% of the irrigation area.

Unlike the majority of rivers that become wider towards the river mouth, the Yellow River narrows. As its width reduces, the Yellow River's discharge capacity also reduces from upstream to downstream. Consequently, the river channel has also been constantly changing, with the mainstream shifting frequently in recorded history. This also causes frequent floods. The flooding area, as far as Tianjing in the North, and the Yangtze River Basin in the south, covers 250,000 km^2. Each time the dyke breaks and the channel shifts, there have been enormous losses in terms of fatalities, sedimentation of farmland leading eventually to desertification, and economic recession. At present, the flood protection areas in the LYR cover a basin area of 120,000 km^2 with a population of 87.5 million. Due to the large area of floodplain between dykes (approximately 2,500 km^2), there are 1.8 million people living within the dykes, who are extremely vulnerable to floods (Li, 2005).

3.1.2 Management Regimes for the Yellow River

For over 2000 years, Chinese emperors in every ancient dynasty regarded the management of the Yellow River as a great task concerning a nation’s stability and prosperity. "Whoever rules the Yellow River rules China," said Yu the Great (2200-2100BC), who is famous for having introduced an effective method of flood control. The Yellow River watered the cradle of Chinese civilization, but also rose in tremendous natural disasters causing floods and droughts. Immense efforts have been made both to control the river to avoid natural disasters, and also to develop it as a resource. Recorded in the History of Former Han, the first major flood in China was caused by a disastrous channel changing of the Lower Yellow River in 2297 BC. Shortly afterwards, *Emperor Yao* appointed the first Minister of water management for the Yellow River. Since 540 BC, there have been 1590 recorded dike bursts along the lower Yellow River, with 26 significant river channel shifts. Due to low precipitation and uneven distribution of rainfall, the river basin has always suffered from serious droughts. According to statistics, from 1766 BC to present, over 1070 major droughts have been recorded. For instance, the 1877-1879 drought lasted 3 years, causing 13 million deaths. The 1929 drought, together with the WWII and the Chinese Civil War between 1927 and 1949, resulted in over 34 million deaths as estimated (Li, 2006).

After 1949, China’s government took the lead in managing the Yellow River. There were two historical strategic approaches to management of the Yellow River, namely, *narrow channel* and *wide channel* strategies. The narrow channel strategy refers to confining the river within high levees. The concept of narrow channel involves encouraging fast flow which keeps sediment in suspension, thus boosting the sediment transport efficiency. This approach, however, increases potential flood vulnerability due to limited reserve capacity for major floods, and so even the high levees will inevitably be overtopped in periods of very high flow. Costs for constructing and maintaining the levees are also enormous. The wide channel strategy works in the opposite way. It suggests making space for floods by confining the river in a wider flood plain. In this case, there is much higher capacity for flood discharge. With small diversion dams, the mainstream can be kept at the centre of the channel, avoiding the problem of scouring of the levee foundations. This option, however, requires that more floodplain area be reserved for flood alleviation, and further promotes silt deposition, which leads to increase in riverbed level. In the 1950s and 1960s, a traditional narrow channel approach was adopted, which involved strengthening and raising the levees. Since the 1960s, a more integrated approach has been implemented to manage the Yellow River, by including engineered spillways and levees set to protect a wider river course. Two tiers of levees were built: an outer set to confine large floods, and an inner one to concentrate the low-flow river and encourage it to scour away its load of silt.

Since 1980s, the runoff in the Yellow River has gradually reduced. In addition to this, fast socioeconomic development following the 1979 China's *Open Door Policy* required much more water resources for agriculture, industrial and domestic uses, whilst increasing amount of wastewater was discharged back to the river without proper treatment. Aiming to restore the river's ecological condition as well as to support socio-economic development, the Yellow River Conservancy Commission (YRCC) developed a new framework in 2004, the *One-Four-Nine-Three* Yellow River Management Strategy. The *One* refers to the new concept proposed, to maintain the healthy life of the Yellow River. The *Four* refers to the four nots objectives: the dike does not breach, the channel does not have zero-flow, the pollution does not exceed the standard, and the riverbed does not rise up (Li, 2005). To achieve this, YRCC proposed *Nine* approaches (as listed in Table 3.2). Finally, the *Three* represents to three technical tools adopted: a numerical model, a physical model, and a comprehensive database of the Yellow River. The numerical modelling institute and the physical modelling laboratories are as seen in Figure 3.2.d. The comprehensive data centre will be established in five years.

Table 3.2 Nine approaches to maintain the health of the Yellow River (Li, 2005)

1	To reduce the sediment load
2	To manage the water resources utilization more effectively
3	To increase the water resources through diverting water from other river basins
4	To build the water and sediment regulating system
5	To work out and execute a scientific and rational general plan for regulating the downstream channel
6	To create a runoff process that does not cause shrinkage of the main channel
7	To adopt water resources protection measures that meet the requirement of water quality functions
8	To harness the estuary of the Yellow River so as to maximally reduce the impacts on the river channel
9	To create a runoff process that meets the requirement of maintaining the benign cycle of the ecological system in the delta region

3.2 Applying PAM to the Yellow River

Two research trips to China were undertaken in 2011 (May to August) and 2012 (July to September). Detailed itineraries are as shown in Appendix I. The purpose of the trips was to apply PAM to examine sustainability of the Yellow River. Visits were paid to the Institute of Environmental Engineering at Peking University (PKU), where a national key laboratory of Water and Sediment Science was based; the Yellow River Institute of Hydraulic Research (YRIHR); the Yellow River Conservancy Commission (YRCC), the government agency under Ministry of Water Resources for managing the Yellow River; the regional offices of the EU-China River Basin Management Programme (RBMP), based at YRIHR; and the Australia China Environment Development Partnership (ACEDP), a research team based at YRIHR. During the trips, main research activities include conducting stakeholder interviews, and collecting various data sets required for calculating river sustainability indicators.

3.2.1 Stakeholder Interviews

The first field trip to China was carried out during May to July in 2011. The purpose of the trip was to apply the first four steps of the PAM method to the Yellow River: firstly, to gain a comprehensive overview of the Yellow River through research site visits and stakeholder interviews; secondly, to develop a working definition of river sustainability (as previously discussed in section 2.3); thirdly, to set up the scope of the case study, including both temporal and spatial boundaries; last but not the least important, based on the impact generators identified through stakeholder engagement, to generate a set of sustainability indicators for the Yellow River. A side from that, various data sets were also collected during the trip for primary analysis.

Intensive stakeholder consultations were conducted at PKU and YRIHR during the research trip. These consultations were conducted in the form of semi-structured interviews, either face-to-face, via telephone calls or emails. A list of the interviews conducted were provided in Table 3.3, including interviewees' names, titles and positions, interview dates and main topics discussed. During the semi-structured interviews, the conversation were structured under six themes: overview of river sustainability, sufficiency, resilience, assess, productivity and equity. A wide range or questions were asked under these themes, Table 3.4 provides a sample list of key questions been asked during the interviews. Depending on the experience and knowledge of the interviewees, either all or a selection of questions were asked during the interviews. The average length of the interviews was an hour, ranging from half an hour to two hours.

Most interviews were carried out in Chinese. This is because, although most interviewees spoke English, they felt more comfortable to communicate in their mother tongue, and more capable of having insightful discussions in Chinese. Extensive notes were taken during the interviews in Chinese, with key information summarized and translated into English by the author, a native speaker of Chinese, after the interviews. Table 3.5 summarises the key information elicited during these semi-structured interviews. However, due to cursoriness in fieldwork planning, these interviews were not recorded therefore full transcripts are not available. Samples of a face-to-face interviews with Prof Jinren Ni, and an email interview (email correspondence) with Mr Simon Spooner were provided in Appendix II.2.

It is worth noting that PAM differentiates from conventional, participatory processes such as stakeholder perception survey, stakeholder roundtable or focus group discussion. PAM does not ask stakeholders to propose a set of possible indicators, or vote for a pre-selected indicators. The main purpose of engaging the stakeholders in PAM was to address the sustainability concerns and emerging challenges of the

Yellow River, to gain understanding of integrated river basin management strategies, and to identify sustainable practices. In this way, PAM help gain a thorough review of the river basin, further identify a complete list the Impact Generators (IGs). The final decision on indicator selection is independently made by the person who conducts the research by using the PAM process (as seen in Figure 2.3). The decision-making process will be discussed in details in the next section. The advantages of using PAM for indicator selection include, first, minimizing stakeholders’ bias; second, avoiding double-counting in the selected indicators; third, enabling a systematic way of indicator selection.

Table 3.3 First-round stakeholder consultation, 2011

Title/Name	*Position*	*Date*	*Type of Interview*	*Topics covered*
Prof. Jinren Ni	Director, IEE, PKU	30/05/2011 17/06/2011; 24/06/2011;	Face-to-face; Telephone	Concepts of river health and river sustainability; Methodologies for assessing sustainability; Composite sustainability indices; Water eco-efficiency and water footprint assessment.
Dr. Xiaoling Mao	Lecturer, IEE, PKU	04/06/2011	Face-to-face;	Methodologies for sustainability assessment; Principles for selecting indicators.
Dr. Tianhong Li	Lecturer, IEE, PKU	07/06/2011	Face-to-face;	River hydrology and river sustainability; Environmental flow calculation;
Dr. Zhengshan Li	Lecture, IEE, PKU	08/06/2011	Face-to-face;	Sediment transport mechanics.
Prof. Wenyi Yao	Director, YRIHR	21/06/2011 25/06/2011	Face-to-face; Telephone	Introduction of YRCC and YRIHR; Introduction of on-going projects with YRCC's affiliated organisations, universities and research institutes; Integrated river basin management strategies; Maintaining healthy life of the Yellow River, the strategies, good practices and objectives.
Mr. Xiaohui Jiang	Chief Engineer, YRIHR	21/06/2011 25/06/2011	Face-to-face; Email	Water resources management and river health; Impacts of hydraulic infrastructure on fish habitats, and biodiversity survey.

Mr. Shaojun Qu	Chief Engineer, YRIHR	21/06/2011	Face-to-face	Sediment issues of the Yellow river; Site survey and river channel capacity of the Yellow River and strategies to enhance sediment transport efficiency.
Prof. Ye’an Zhao	Senior Advisor, YRIHR	22/06/2011	Face-to-face	Historical management regimes of Yellow River basin; Implementation of integrated river basin management strategies.
Mr. Yan Wu	Director, HYKGauging Station	22/06/2011	Face-to-face	Introduction to Huayuankou hydraulic station; Hydraulic data acquisition; Flood control and flood warning systems.
Mrs. Xiaoping Li	Researcher, YRIHR	22/06/2011	Face-to-face	Site survey and observations of the changes of river channel; Role of Xiaolangdi Dam in regulating water and sediment.
Prof. Shengli Zhang	Senior Advisor, YRIHR	23/06/2011	Face-to-face	Role of water and soil conservation in the Yellow River; Capacity building for integrated river basin management.
Mr. Pu Qi	Senior Advisor, YRIHR	23/06/2011	Face-to-face; Email	Strategies for improving sediment transport efficiency; Implementation of integrated river basin management strategies.
Mrs. Liu	Consultant, YRIHR	24/06/2011	Face-to-face	Physical model laboratory of the Yellow River;
Mr. Zhengzhou Sheng	Researcher, YRIHR	24/06/2011	Face-to-face	YRIHR library and online database, data availability
Mr. Simon Spooner	Pricipal Engineer, Atkins Global	10/2011-01/2012	Email	EU-China River Management Scheme; Implementation of river health assessment for the Yellow River

Table 3.4 List of sample questions for the Stakeholders’ Interviews

Overall

1. What are the characteristics of the Yellow River?
2. What distinguishes the Yellow River from other rivers?
3. Please summarize the most pressing issues concerning the Yellow River?
4. What are the challenges to management the Yellow River?
5. Can you explain the integrated river basin management strategies for the Yellow River?
6. What are the short-term and long-term goals of the management of Yellow River?
7. Please explain the policy of “maintaining river health of the Yellow River”.
8. What does a sustainable river course means to the Yellow River?
9. How do you think river sustainability differentiates from river health?

Sufficiency

10. Please explain the flow regime of the Yellow River. Has there been sufficient environmental flow in the Yellow River, and why?
11. Has the water quality in the Yellow River improved or degraded, and what are the possible reasons?
12. Please explain the major point source and non-point sources of wastewater discharged to the Yellow River.
13. What are the issues with excessive sediment in the Yellow River?
14. What are the solutions to the high sediment load and what are the achievements?
15. Please explain the water and soil conservation strategies being applied to the LYR.
16. Is there any evidence of biodiversity or habitats loss in the Yellow River basin?
17. What’s the status of, and change to forests, floodplain and wetland in the Yellow River basin?
18. Please explain the land use and conservation policies to the Yellow River basin.

Resilience

19. Please explain the flooding issues and risks with the Yellow River.
20. Please explain the drought issues and risks with the Yellow River.
21. Please explain water pollution and water quality degradation issues with the Yellow River.
22. Please explain if any public health risks associated with water contamination, and water-borne diseases.
23. Please explain the role of early warning systems in managing the risks.
24. Please explain the implementation of water and sediment regulation policy.

Access

25. Please explain the development of water supply and wastewater treatment facilities in the Yellow River basin
26. Please explain the development of sanitation facilities and public sewage system in the Yellow river basin.
27. What are the impacts on social wellbeing?

Productivity

28. Please explain the development of multi-functional infrastructures on the Yellow River.
29. What are the impacts of multi-functional infrastructure?
30. Please explain the average domestic water consumption in the Yellow River baisn, and if any water conservation campaigns.
31. Please explain the agricultural activities in the Yellow River basin.
32. Please explain the water intensive industries activities in the Yellow River basin.

Equity

33. What are the competing needs of water in the Yellow River basin?
34. Please explain the Yellow River Water Allocation policy (1987), and the implementation of the plicy
35. Please explain the practices of water permits trading in the Yellow River Basin.

Table 3.5 Summaries of stakeholders' opinions during first fieldtrip to China

Stakeholder	*Key information*
Prof Jinren Ni	*Characteristics of the Yellow River* Yellow River is called mother river of China, it's the cradle of Chinese civilization. Yellow River basin is one of the most highly populated river basin in the world. The Yellow River is also known for excessive sediment load. The issues associated with high sediment load include river channel in the lower reaches siltation, relocation of river course, and consequently extreme floods (Ni, pers comm., 2011).
	River Health of the Yellow River The concept of river health conveys the message of maintaining and restoring the natural structure and functions of a river and its catchment. The term health simply means good condition. It treats the river basin as a whole, like a person, and helps provide an overview of the status of the river, which is particularly useful for policy-makers to underpin policies for integrated river basin management (Ni, pers comm., 2011).
	Management challenges For thousands of years, the challenges to management the Yellow River are to alleviate flood and drought risks, to transport sediment in an efficient way, and to utilize the limited water resources for human use. In the context of climate change and fast growing economy, new challenges emerges, including dealing with increasing uncertainties in annual renewable water, balancing the supply and demand for water, preventing the water quality and river ecosystem from degradation, and allocating water to different provinces and different sectors in an equitable manner (Ni, pers comm., 2011).
Dr Xiaoling Mao	*Indicator based assessment* A River Health Index for the Yellow River was developed by PKU. The selection of indicators are based on reviewing nine major functions of a river system, namely, flood discharge, sediment

	transport, ecosystem support, self-purification, water abstraction, hydropower generation, navigation, and recreation. Weights are applied to these indicators by using the Analytic Hierarchy Process, These indicators were then aggregated to form the River Health Index (Mao, pers comm., 2011).
Dr Tianhong Li	*Interconnected challenges of droughts and floods* Yellow River has been running dry in the past half century. Average annual renewable water resources has been decreased from 5.8 BCM to 5.2 BCM. Lower Yellow Basin experienced extreme droughts in the 1990s. Lijin station for instance, 220 days in a year (1997) there was no flow in the Yellow River. This devastated the river ecosystem, and caused extreme water tension for the people who depend on water supply from the Lower Yellow River. Yet, the prolonged droughts decreased the river channel capacity due to siltation. In addition, social settlement was built in the floodplain. This significantly increases the vulnerability to extreme events (Li, pers comm., 2011a)
Dr Zhengshan Li	*Sediment transport* How to transport sediment in an efficient way has been a key questions to maintain healthy life of the Yellow River. Both numerical model and physical model have been built to analyse the dynamics between flow and sediment. Xiaolangdi Reservoir was established in 2001, has significant impacts on sediment transportation. It regulates flow in the LYR during the flood seasons, and can release a discharge of 5000 m^3/s during the non-flood seas to reduce deposition and maintain/improve the channel capacity (Li, pers comm., 2011b).
Prof Wenyi Yao	*Integrated River Basin Management* YRCC takes the lead of integrated river basin management. Firstly, seven large-scale multi-functional infrastructures are being built on the mainstream of the Yellow River (five completed, including Xiaolangdi; another two will be completed by 2015). They enable YRCC to regulate water allocation, capture excessive sediment,

	improve sediment transport efficiency and generate hydropower. Secondly, a physical model laboratory (as seen in Figure 3.2d) and a numerical modelling institute of the Yellow River have been founded. These play a crucial role in monitoring the flow and sediment dynamics in the river, and the prediction of flood and drought events, as well as providing an early warning system (Yao, pers comm., 2011).
	Sustainability concerns Emerging challenges to the management of Yellow River are associated with fast socio-economic development. Floodplains are intensively used for agricultural, industrial or residential purposes. Potential flooding events therefore pose a much higher threat to social well-being, comparing to half a century ago. Another challenge is the consistent decline of renewable water resources. There is huge deficit between supply and demand. It is crucial to utilize water resources in an efficient way, to regulate water abstraction and to improve water use efficiency (Yao, pers comm., 2011).
Mr Pu Qi	*Multifunctional infrastructures* Xiaolangdi reservoir is a very successful case of regulating water and sediment. In the late 1990s, the LYR was running dry. For instance, Lijin gauging station witnessed no flow for over 200 days in 1997. Since Xiaolangdi started functioning in 2001, the LYR has experienced continuous flow. Sediments trapped by the Xiaolangdi reservoir are flushed several times a year with maximum water-sediment transport efficiency. However, the Xiaolangdi reservoir has had a huge impact on the river ecology. Studies on biodiversity are being carried out. Lifespan of Xiaolangdi Reservoir must also be taken into account, due to the fact that it will silt up in approximately 50 years' time (Qi, pers comm., 2011).
Mr Shengli Zhang	*Water and soil conservation* Water and soil conservation activities are concentrated in the mid reaches of the Yellow River. To deal with excessive sediment in the

	Yellow River, it is crucial to control the source of sediment from the Loess Plateau. Local activities including afforestation, farmland restoration and the construction of check dams have helped to reduce substantially the amount of sediments discharged to the Yellow River (Zhang, pers. Comm., 2011)
Mr Simon Spooner	*Defining River Sustainability* The big goal would be to formulate a definition of river quality and status that embraces the fact that for modern society the ideal outcome is not to return the river to some mythical unspoiled reference condition but to farm the river such that it sustains the most healthy ecosystem that can purify itself and sustain the human society dependent on it in the most healthy manner over the long term. This means well managed, not polluted beyond its capacity to self-purification and the morphology and flow regime managed to sustain healthy and diverse ecosystem - Basically maximise eco system services delivery. In addition to the management of flood, drought, sediment, pollution risks etc. (Spooner, pers comm., 2011).
	River Sustainability Index The Composite River Sustainability Index is a good idea. However it is always difficult to decide on what the parameters to include should be. Hence under WFD in EU the vague "good ecological status" target then years of wrangling about what it means. In China the River health assessment is the system currently under development by MWR to be a formal assessment system. This will incorporate statutory/policy targets such as *Three Red Lines* that then link to administrative official's personal performance assessments (and so promotion/remuneration opportunity). This aspect of strategy is set out in the No. 1 policy document on accelerating investment in water. MWR guidelines on river health assessment are currently being piloted and under review (Spooner, pers comm., 2011).

Set up the System Boundary

From the literature review and stakeholder interviews, we found different reaches of the Yellow River have distinctive characteristic and sustainability issues. Therefore, the indicators generated from PAM would not apply to the entire Yellow River basin, and sustainability assessment needs to focus on one reach/region to deal with the specific sustainability challenges. The lower reach of the Yellow River (LYR) is chosen as geographical extent of our assessment for the following two reasons: first, LYR is the most highly populated reach of the Yellow River with the fastest growing economy; and second, this section of river faces most of the challenges identified, including, siltation in river channel, water quality degradation, floods, droughts, increasing demand for water and intensive infrastructure development. Geographical boundary of the LYR basin, with locations of the the major resoirvis (Kong et al., 2015).

The temporal boundary of our assessment covers the period from 1950 to 2010. 1950 is the first year after the People's Republic of China was founded, since then various data became available. The temporal boundary is considered broad enough to reveal inter-generational changes towards sustainability.

3.2.2 Site Visit to the Lower Yellow River

During the research trip in 2011, a road trip was undertaken along the Lower Yellow River (LYR) accompanied by senior researchers from YRIHR. The purpose of the trip was to gain better knowledge of the status of LYR from site observations.

The trip started from Huayuankou gauging station, which is located at the beginning of the standard dykes along the LYR, the journey covered a 150 km reach of the river.

The visit enabled inspection of riverside facilities, dams, levees and the central channel. Standard dyke is the flood defence built along the riverbanks by YRCC, which is regulated by stringent standards (see Figure 3.2.1 and Figure 3.2.2). Being constructed since 2005, the standard dyke now function as flood defences, transportation hubs, and ecological restoration sites (YRIHR and CAS, 2009). Following the *wide channel strategy* of the YRCC, the distance between the dykes varies from 1 km to 12 km along the LYR (Li, 2006). This raises a major concern regarding flood-prone villages located in the floodplain between the dykes. Some of these villages have been in existence for more than one hundred years. People living in these villages are reluctant to be displaced away from the floodplain, owing to their perception that they are unlikely to experience flood events in the future owing to the scarcity of recent floods accompanied by the significant reduction in runoff (Li, pers comm., 2011). According to YRCC (2006), there is an estimated 3 million population living in these flood-prone villages in the LYR. Social and economic activities in these villages, including agriculture, fishery and tourism, were observed. During the visit, we also found evidence of frequent shifts of LYR mainstream (Figure 3.2.3).

a. Standard Dyke along LYR

b. Flood defense infrastructure (levees) built in 2005 along LYR, with a length of 300km

c. Cross-section survey from a float bridge near Gaocun

d. Physical modelling laboratory of YRIHR

Figure 3.2 Photographs taken during field trip to the LYR

3.2.3 PAM for Indicator Selection

Insights into the Yellow River's sustainability challenges have been gained through literature, stakeholder interviews and site visits. A set of Impact Generators (IGs) for LYR was identified. In PAM, IG refers to a factor which makes notable impacts on sustainability, either from internal of the system (IIGs), or external (EIGs). IGs presents fundamental understanding of the complex system we study.

Table 3.6 List of impact generators on Yellow River's sustainability performance

Sustainability Perspectives	*Impact Generators (IGs)*
Sufficiency	Varying flow rate and flow patterns Varying water quality Varying sediment load Water and sediment conservation Aquatic and wetland restoration Wastewater management and water pollution control
Resilience	Land use policy Floodplain and wetland restoration Flood defense infrastructure development Public health policy
Access	Water abstraction management Water allocation management Water utilities development and management Sanitation and sewage system development and management
Productivity	Water use efficiency management Multi-functional infrastructures development Hydropower generation management Financial investment
Equity	Water allocation management and water permits trading; water resources planning and cross-boundary water transfer

Based on the IGs, the sustainability assessment framework for the LYR has been developed by applying the PAM process. Table 3.7 to Table 3.9 shows how PAM is used for indicator selection towards LYR's environmental performance, social welling and economic development. This leads to a tailored set of sustainability indicators, as shown in to Table 3.10.

Table 3.7 PAM for indicator selection for LYR's environmental performance

IIGs	*Impact on*	*Issue*	*Concern*	*EIRs*	*Indicator*
Varying flow rate	Environmental flow	Insufficient flow to sustain river ecosystems and the human livelihoods and wellbeing that depend on these ecosystems.	*Sufficient* flow	Current generation	Environmental flow
		Increasing uncertainty and scale in seasonal flow variation.	*Resilience* to flow variation	Current and future generations	Environmental flow
Varying water quality	Water quality	Water quality degradation. Unable to meet the requirement for maintaining ecosystem health.	*Sufficient* supply of usable water resources	Current generation	Water quality
Varying flow and sediment load	Sediment transport	Insufficient sediment transport efficiency, resulting in sediment deposition, siltation of river channel and reservoirs.	*Efficient* transport of sediment	Current generation	Sediment transport
Water and sediment	River channel capacity	River channel erosion and decrease in flood discharge capacity. This could further cause shifts of river course and increase flood risk.	*Sufficient* discharge capacity; *Resilience* to varying physical form of river channel	Current generation	River channel capacity
Aquatic and wetland restoration	Biodiversity	Changing water environment for aquatic species; habitat destruction for wetland species	*Resilience* to varying aquatic species and biodiversity loss; intergenerational *equity*	Current and future generations	Biodiversity

Floodplain and wetland management	Land use	Loss of floodplain and wetland, resulting in increasing flood risk and habitat destruction for wetland species.	*Resilience* to varying habitats and ecological cycle.	Current and future generations	Land use

Table 3.8 PAM for indicator selection for LYR’s social wellbeing

IIGs	*Impact on*	*Issue*	*Concern*	*EIR*	*Indicator*
Varying flow rate	Flood risk	Increasing flood risk due to changes in flow pattern and decrease in channel capacity.	*Resilience* of people and built environment to increasing flood risk.	Current and future generations	Flood risk
Land use policy (including urbanization)	Location and types of settlement	Increasing potential flooding damage due to increasing population density and commercial use of floodplain.	*Resilience* of people and built environment to increasing flood risk.	Current generation	Flood risk
Varying flow rate	Drought risk	Increasing functional no-flow days, affecting human use of water and causing irreversible damage to both river ecology	*Resilience* to increasing drought risk.	Current and future generations	Drought risk
Water abstraction management	Water provision to population	Abstraction of water resources exceeds water resources renewable rate.	*Sufficient* water provision and intergeneration *equity*	Future generations	Water abstraction
Water allocation management	Water allocation	Water allocation among different uses in terms of domestic, agricultural and industrial uses, and	*Equity* between different users, and uses for different purposes.	Current generation	Water allocation

		between upstream and downstream users.			
Water consumption management	Water use efficiency	Inefficient use of limited, renewable water resources	*Productivity* of water resources	Current generation	Water consumption
Water utilities management	Water supply	Access to safe drinking water supply.	*Access* to public water supply, as human right to water	Current generation	Water supply coverage
	Sanitation and sewage	Lack of access to modern sanitation facilities and urban sewage system.	*Access* to modern sanitation and public sewage system.	Current and future generations	Sanitation and sewage coverage
Water pollution control management	Wastewater discharge and water quality	Lack of wastewater treatment capacity for industries and urban areas, resulting in excessive wastewater discharged to the river, causing water quality degradation	*Sufficient* wastewater treatment capacity	Current and future generations	Coverage of treatment (%)
Public health management	Public health	Lack of prevention and early warning facilities for water contamination incidents; lack of treatment capacity for waterborne disease	*Resilience* to water contamination incidents	Current generation	Public health

Table 3.9 PAM for indicator selection for LYR's economic development

IIGs	*Impact on*	*Issue*	*Concern*	*EIR*	*Indicator*
Water utilities development	Water use efficiency	Sufficient financial capacity to improve and maintain water supply for agricultural, industrial and domestic uses.	*Productivity* of water resources	Current and future generations	Financial capacity
	Sanitation and wastewater management	Sufficient sanitation coverage and capacity for wastewater treatment.	*Sufficient access* to wastewater treatment facilities		Financial capacity
Multi-functional Infrastructures development	Water and sediment regulation for IRBM	Limited water storage capacity for regulating sediment transport.	*Productivity* of sediment transport	Current and future generations	Multi-functional infrastructure
Flood defence infrastructure development	Flood risk management	Limited scale/length of standard dyke for flood-prone areas.	*Resilience* to increasing flood risk.		Flood defence
Hydropower development	Hydropower generation	Lack of hydropower generation capacity to meet the needs of socioeconomic development.	*Productivity* of water resources.	Current and future generations	Hydropower generation
Financial investment	Public awareness campaigns, water-related education and institutional capacity for IRBM	Limited investment in public awareness campaigns, water-related education and institutional capacity building for IRBM.	*Productivity* of water resources.	Current and future generations	Institutional capacity

Table 3.10 Sustainability indicators and sub-indicators for the Yellow River by PAM

Indicators	*Measurements*	*Metrics*
Environmental Performance Domain		
Environmental flow	Discharge of the LYR at Huayuankou Station	m^3/s
Water quality	Ratio of LYR meets the minimum usable water resources requirement	%
River channel capacity	LYR flood discharge capacity	m^3/s
Sediment transport	Annual sediment load	10^9 m^3/yr
Biodiversity	Number of Aquatic Species	Number
Land use change	Changes in floodplain, wetland areas and soil erosion areas (increased/restored)	%
Social Wellbeing Domain		
Flood risk	Number of total days of floods in the given year	Number/yr
Drought risk	Number of functional no-flow days in a year	Number/yr
Water consumption	Annual water abstraction	10^9 m^3/yr
Water access	Percentage of population with access to drinking water	%
Wastewater discharge	Percentage wastewater treated in gross wastewater discharged.	%
Water allocation	The extent to which the *1987 Yellow River Water Allocation Plan* is achieved	%
Public health	Number of people exposed to flooding, drought and water contamination incidents	Number/yr
Economic Development Domain		
Multi-functional infrastructures	Water storage capacity of major reservoirs	10^9 m^3
Hydropower development	Hydraulic power generation capacity	10^9 kWh/yr
Water supply utilities	Water supply capacity	10^9 m^3/yr
Wastewater treatment utilities	Wastewater treatment capacity	10^9 m^3/yr
Institutional capacity	Annual financial input in education and institutional capacity building	10^9 Yuan/yr

3.2.4 Verification of the Assessment Framework

The second field trip to China was carried out during in 2012. Visits were paid to PKU and YRIHR, with detailed itineraries and supporting documents can be found in Appendix I. The main purpose of the trip was to complete the final step of PAM, to verify the assessment framework. Key stakeholders were interviewed during the visit, to give their opinions on the selected indicator set (see Table 3.10). Various data sets were collected during this trip for calculating the indicators.

Verification of the assessment framework involves stakeholder consultation. Ideally, this process should be done through a focus group discussion, if the key stakeholders were able to meet at the agreed time and venue. In our research, such workshop was unable to be carried out, due to limited availability and different locations of our stakeholders. Instead, key stakeholders were interviewed either face-to-face or via email or phone calls, to give their opinions on the assessment framework. During the interviews, key stakeholders were asked the question: “What’s your personal opinion, in a few sentences, on the river sustainability assessment framework for the Yellow River?”. This was designed to force a succinct judgement. More feedback was gained during the 5th International Yellow River Conference in Zhengzhou, where the assessment framework for measuring sustainability of the Yellow River was presented to a wider audience at the conference. Some of the key stakeholders from YRIHR who participated in the first-round stakeholder consultation attend the presentation, as well as water managers, experts from other research institutes or university. Comments and feedback were received following the presentation. These comments and feedback were summarized in Table 3.11.

Table 3.11 Summary of judgments from the second-round stakeholder consultation, 2012

Title/Name	*Position*	*Date*	*Type of Interview*	*Opinions*
Prof. Jinren Ni	Director, IEE, PKU	30/08/2012	Face-to-face;	The assessment framework presents a comprehensive and well-structured indicators set, which is the result of thoughtful consideration of literature and stakeholders' views on sustainability of the Lower Yellow River. It covers much broader aspects comparing to the River Health Index, and provides a holistic view on the three domains of sustainability. The challenge lies in how to use existing, limited data to measure what it proposed to measure. Justification must be made i.e. where *surrogate indicators* are to be used (Ni, pers comm., 2012).
Dr. Tianhong Li	Lecturer, IEE, PKU	31/08/2012	Face-to-face;	The work clearly shows how river sustainability is defined, how PAM leads to a holistic set of indicators. Yet, some of the measurements need to be enhanced, to give accurate and convincing results. My expertise is specialised in environmental flow assessment and flood modelling. For the *environmental flow indicator*, I recommend an integrated flow deviation index to capture the characteristics of the flow (Li, pers comm. 2012).
Dr. Xiaoling Mao	Lecturer, IEE, PKU	1/09/2012	Face-to-face	A comprehensive set of indicators for Yellow River's sustainability study. You need to argue how it is different from existing measures i.e. the River Health Index, and what's the potential usefulness of the framework. And potential to apply this to other river basins, to enable cross-basin comparison (Mao, pers comm., 2012).

Prof. Wenyi Yao	Director, YRIHR	23/092012	Telephone	The proposal indicator set is well presented under three domains of sustainability, and each of the indicator has clearly stated what it measures and how. Yet, measurements for some indicators need to be advanced: *flood risk* is not just associated with the flood duration. The damage of the flood also depends on flood scale, which can be measured by flood volume. With regard to the *public health indicator*, it should focus on water-related public health issues (water contamination), rather than double accounting the impacts of floods and droughts (Yao, pers comm., 2012).
Mr. Xiaohui Jiang	Chief Engineer, YRIHR	23/09/2012	Face-to-face	A state of the art selection of indicators. The framework has well presented the PAM method. The difficult inherent in applying such a comprehensive indictor-based assessment is data scarcity and data gaps. For instance, large-scale biodiversity survey has only been conducted three times since 1980. No early data is available, and the way in which the survey was done has been changed over time. Therefore, how to use the existing, inconsistent data to make meaningful measurement needs careful consideration. Also, *the biodiversity indicator* should include a set of sub-indicators, measuring fish species, zoo benton and phytoplankton respectively (Jiang, pers comm., 2012).
Mr. Simon Spooner	Pricipal Engineer, Atkins	14/09/2012	Face-to-face; Email	This framework shows a step forward comparing to the River Health Reporting Card (by ACEDP), which monitors the status of river health based on existing indicators and data. This river sustainability assessment framework helps identify the gaps – between what is monitored and what needs to be measured (Spooner, pers comm., 2012).

Final changes were made to the assessment framework after the second-round stakeholders' consultation. Taken stakeholder's comments into account, measurements for the following indicators have been updated, including, the environmental flow indicator, biodiversity indicator, flood risk indicator and public health. The final indicator set is presented in Table 3.12.

It is worth mentioning that, firstly, although PAM is a participatory approach, the decision on which indicator to keep or omit is made by the researcher through the process of PAM, not based on votes from stakeholders. This process enables the decision making through PAM to be systematic, and not affected by stakeholders' bias. Secondly, the selection of indicators and measurements are not based on data availability. The researcher took independent review following PAM, the assessment framework indicates what needs to be measured, instead of what can be measured. This, indeed, introduces the issues with data scarcity. However, it identifies the gaps, highlights the areas where data is missing, points out where future work is needed.

Table 3.12 Verified Sustainability Assessment Framework for the Lower Yellow River

Notation	*Indicators*	*Sub-indicators/Measurements*	*Metrics*	*Changes made in response to Stakeholder's comments*
Environmental Performance Domain				
EP$_1$	Environmental Flow Indicator	High-flow volume (HFV)	m^3	According to Li's comment (Li, pers comm., 2011), the measure of environmental flow by flow discharge is replaced by the flow deviation index, consisting of four sub-indicators.
		Highest monthly flow (HMF)	m^3/s	
		Low-flow volume (LFV)	m^3	
		Lowest monthly flow (LMF)	m^3/s	
EP$_2$	Water Quality Indicator	Ratio of monitored river section meets the minimum usable water resources requirement, the Chinese national surface water quality standard III	%	
EP$_3$	River Channel Capacity Indicator	Flood discharge capacity of the Lower Yellow River	m^3/s	
EP$_4$	Sediment Transport Indicator	Annual sediment load in the Lower Yellow River	10^9 m^3/yr	
EP$_5$	Biodiversity Indicator	Zoo benthos (number of species)	Number	Three sub-indicators are used to specify different aquatic species (Jiang, pers comm., 2011).
		Phytoplankton (number of species)	Number	
		Fish (number of species)	Number	
EP$_6$	Land Use Indicator	Changes in natural wetland areas	%	
Social Wellbeing Domain				
SW$_1$	Flood Risk Indicator	Frequency of flood events in terms of total days of floods in the given year (FF)	Number/yr	Flood risk is associated with both magnitude and frequency of flood events (Yao, pers comm., 2011). Therefore, FF and FV sub-indicators
		Flood volume by Peak-over-threshold method (FV)	m^3	

				are introduced to capture/represent the complexity of flood risk.
SW_2	Drought Risk Indicator	Number of functional no-flow days in a year	Number/yr	
SW_3	Water Consumption Indicator	Annual water consumption in LYR	10^9 m^3/yr	
SW_4	Water Access Indicator	Percentage of population with access to drinking water	%	
SW_5	Wastewater Discharge Indicator	Percentage wastewater treated in gross wastewater discharged.	%	
SW_6	Water Allocation Indicator	The extent to which the 1987 Yellow River Water Allocation Plan is achieved	%	
SW_7	Public Health Indicator	Number of people affected by water contamination incidents	Number/yr	The number of people affected by flood and drought are no longer included, due to limited relevance (Yao, pers comm., 2011).
Economic Development Domain				
ED_1	Water Infrastructures Indicator	Water storage capacity of major reservoirs of key multi-functional water infrastructures	10^9 m^3	
ED_2	Hydropower Indicator	Total hydraulic power generation capacity	10^9 kWh/yr	
ED_3	Water Supply Indicator	Total annual water supply capacity of LYR	10^9 m^3/yr	
ED_4	Wastewater Treatment Indicator	Wastewater treatment capacity	10^9 m^3/yr	
ED_5	Financial Capacity Indicator	Annual financial input in managing LYR	10^9 Yuan/yr	Financial input in water-related education is no longer counted due to limited relevance (Yao, pers comm., 2011).

3.2.5 Data Collection

Large quantities of data are needed to deliver an indicator-based assessment for sustainability. Since beginning of the research, much effort has been made to investigate data availability and to collect data. Primary data sources for the present research include: the Ministry of Water Resources (e.g. Five-Year Plan of national water resources development, China water resources yearbook, Annual statistic bulletin on China's water activities), the National Bureau of Statistics (e.g. the China statistical yearbook); YRCC and YRIHR (e.g. Annual water resources bulletin of the Yellow River, Annual sediment bulletin of the Yellow River, Monthly water quality report of the yellow River, YRIHR hydrological database, raw data from ecological survey and wetland survey); PKU (previous and on-going researches, GIS database of the Yellow River); and publications and journal papers.

Raw hydrological data sets for 51 locations along the Yellow River were obtained from PKU, whose staff members have been working on various research projects on hydraulic modelling and sediment transport mechanics of the Yellow River. The available data sets include sediment transport rate, daily average discharge, and water level for each location. We selected three hydrological stations in the Lower reaches of the river basin for the study: Huayuankou, Gaocun, Aishan, and Lijin, as shown in Figure 3.3. For certain indicators, such as the environmental flow indicator, analysis was also conducted of data from stations in the Upper and Middle Reaches (Lanzhou, Toudaoguai) in order to reveal the correlation between different sessions of the river.

Figure 3.3 Map of LYR from Sanmenxia to Bohai Sea (Borthwick, 2005)

Matlab programs (2011, 2013 versions) are used to process the raw data to a chronological string of average daily or monthly discharge time series. For instance, data in tabular format with rows and columns corresponding to month's days respectively are converted into a single column string of daily discharge values. Several gaps in the data were identified. These will be discussed further in section 3.4 – 3.6, concerning the calculation of indicator values.

3.3 Environmental Performance of LYR

3.3.1 Environmental Flow Indicator EP_1

Approaches to environmental flow assessment can be categorized into three groups: historical flow analysis, hydraulic method, and habitat method (Jowett, 1997). The historical flow method reveals the relationship between the flow condition and existing ecology by using historical hydrological data (Tennant, 1976), while the other two methods incorporate cross-sectional survey information to assess the impact of water ecology on habitats (Tennant, 1976, Arthington et al., 1992) . To keep the present environmental flow indicator independent of the biodiversity and land use indicators, the Integrated Flow Deviation method (IFD), based on Tennant’s method, is chosen to calculate the environmental flow indicator.

IFD is based on the natural flow variation in a river system. The first step is to identify the critical threshold for monthly flow, by analysing flow regime characteristics (Richter, 1997). For the Lower Yellow River, the inter-quartile range of 25th to 75th percentile is adopted for the water security boundaries, refering to YRCC’s research on flow regime (YRCC, 2009; Gippel et al., 2011). The IFD method is based on four sub-indicators: high flow volume (HFV), low flow volume (LFV), highest monthly flow (HMF), and lowest monthly flow (LMF). The IFD is then calculated as the mean value of the four individual indicator scores. The score of these indicators will be calculated independently, then normalized to a value ranging from 0 to 1, with 1 representing a low degree of deviation in the indicators.

To apply the IFD assessment, *the hydrological year* needs to be determined. Although many hydrological statistics such as rainfall are reported for the calendar year, the hydrological year usually does not coincide with the calendar year. The reason for introducing the hydrological year is to avoid splitting the high flow season between consecutive years, in this case, the month with the lowest mean discharge may be the ideal start of the water year, a method designed by Gordon (2004). The hydrological year is therefore split into two six-month seasons. The beginning month of the low flow season (and the start of the hydrological year) is determined as the first month of the sequence of six months with the lowest sum of median monthly flows. Table 3.5 illustrates the process of determining the hydrological year of the LYR, based on hydrological statistics of HYK gauging station. The mean monthly flow is calculated for each month for the reference period. For each month, the sum of the following 6 months' flow is calculated. The month with the smallest sum is the start of the water year (Gippel et al., 2011). In this case, December with lowest following 6 months' flow is identified as the start of a water year of LYR.

Table 3.13 Calculation of the hydrological year of LYR

Month Flow volume (10^9 m^3)	Jan	Feb	Mar	Apr	May	Jun
Mean monthly flow	1.45	1.33	2.64	2.63	2.54	2.16
Following 6 months' flow	12.75	16.13	21.72	25.39	28.13	28.7
	Jul	Aug	Sep	Oct	Nov	Dec
Mean monthly flow	4.83	6.92	6.31	5.36	3.12	1.96
Following 6 months' flow	28.5	36.41	45.62	15.85	13.12	12.54

The next step is to establish the reference distributions and thresholds, including flows for each month, low flow period total flows, high flow period total flows, maximum monthly flow and minimum monthly flow.

Table 3.14 Flow deviations at Huayuankou

Flow volume (10^9 m^3) Year	Low Flow period total	High flow period total	Maximum month flow	Minimum month flow
1950	140.02	328.30	86.38	15.19
1951	134.61	354.78	86.57	15.67
1952	144.35	306.22	85.60	14.78
1953	110.25	326.62	101.80	14.22
1954	127.44	458.59	144.60	15.39
1955	147.79	425.59	98.76	17.01
1956	113.60	360.39	114.10	12.53
1957	113.37	244.11	89.73	13.79
1958	97.66	532.25	156.70	9.15
1959	94.17	296.71	109.30	8.89
1960	51.68	149.26	65.62	1.73
1961	132.89	426.83	100.70	2.97
1962	158.69	290.04	83.57	11.79
1963	167.22	389.94	96.96	8.27
1964	213.03	648.38	145.70	8.44
1965	170.62	212.77	66.42	13.18
1966	97.45	355.09	98.24	4.20
1967	166.03	539.96	147.70	7.74
1968	200.28	384.95	109.40	12.50
1969	145.56	158.51	43.80	6.70
1970	132.22	237.96	67.91	10.77
1971	122.05	229.36	61.07	6.00
1972	124.33	170.46	42.05	11.92
1973	94.71	266.44	69.98	7.19
1974	115.01	168.90	48.21	8.56
1975	121.41	427.95	126.70	12.57
1976	139.57	394.38	127.80	16.18
1977	123.88	225.47	69.10	9.99
1978	88.06	261.86	88.91	6.27
1979	121.66	250.00	79.82	9.49
1980	103.41	188.74	46.60	8.97
1981	92.39	384.23	125.50	5.24

1982	125.23	301.73	105.30	13.72
1983	138.08	472.34	120.30	14.35
1984	143.53	391.92	103.10	12.58
1985	144.42	329.63	98.24	17.65
1986	123.58	168.31	60.80	10.39
1987	92.62	135.32	28.51	11.90
1988	102.08	254.43	102.30	9.60
1989	161.14	264.31	80.87	18.53
1990	163.76	200.95	42.32	17.76
1991	133.55	107.87	40.18	8.55
1992	95.85	171.44	59.19	6.59
1993	130.35	174.78	58.12	10.11
1994	134.03	171.23	51.96	9.12
1995	100.51	138.48	45.10	3.97
1996	88.72	188.59	72.75	7.98
1997	84.52	58.03	26.52	3.40
1998	79.01	138.96	40.44	6.35

To normalize the sub-indicators, the scores for HFV, LFV, HMF and LMF are calculated according to a basic standard for hydrological parameter (Gippel et al., 2011):

- If the natural flow series fall within the inter-quartile range (25th to 75th per centile), all the hydrological indicator sub-indicator (HFV, LFV, HMF and LMF)

$$\text{Score} = 1 \qquad (3.1)$$

- If the percentile in parameter distribution falls in the range $> 75^{th}$ percentile, High flow season sub-indicators (HFV, LMF)

$$\text{Score} = 1 \qquad (3.2)$$

Low flow season sub-indicators (LFV, LMF)

$$\text{Score} = 1.75 - {percentile\,in\ \ distrubution}\big/_{100} \qquad (3.3)$$

- Percentile in parameter distribution in the range $< 25^{th}$ percentile, High flow season sub-indicators (HFV, LMF)

$$\text{Score} = 4 \times \text{percentile in distribution} / 100 \qquad (3.4)$$

Low flow season score sub-indicators (LFV, LMF),

$$\text{Score} = 1 \qquad (3.5)$$

The integrated score fo the Environmental Flow Indicator is the mean of the four sub-indicators (equal weighting for all the sub-indicators),

$$EP_{1,i} = \frac{1}{4}\left(HFV_i + LFV_i + HMF_i + LMF_i\right) \qquad (3.6)$$

where $EP_{1,i}$ means the score for the Environmental Flow Indicator (the 1st indicator under Environmental Performance Domain), in given year *i*; and HFV, LFV, HMF, LMF are scores of the four sub-indicators for environmental flow deviation in the given year *i*.

For the period from 1998 to 2010, due to lack of daily/monthly discharge data, the deviation of annual discharge is used as a surrogate to calculated the environmental flow indicator:

- If annual flow volume falls in the range of 75% to 125% of mean annual discharge *MFV*,

$$EP_{1,i} = 1 \qquad (3.7)$$

- If annual flow volume falls in the range of 25% to 75% or 125% to 175% of *MFV*,

$$\mathrm{EP_{1,i}} = 2\left|\mathrm{FV_i} - \mathrm{MFV_i}\right| / \mathrm{MFV} \qquad (3.8)$$

- If annual flow volume is either no greater than 25% or exceeds 175% of *MFV*,

$$EP_{1,i} = 0 \qquad (3.9)$$

where $EP_{1,i}$ is the score for the Environmental Flow Indicator in given year i;

MFV as the mean annual discharge (flow volume) in for the period of 1950 to 2000, namely, 40.53 BCM.

Flow deviation scores for the four hydrological stations and the final aggregated results of are shown in Figure 3.8. It shows large variations over the study period, with unsustainability status identified between 1985 and 2000. The situation gradually improved since 2000.

3.3.2 Water Quality Indicator EP_2

Surface water quality in China is regulated by the Environmental Quality Standards for Surface Water in China (GB3838-2002). This standard is applicable within the territory of rivers, lakes, canals, irrigation channels, reservoirs and other surface water features with the use of the waters. This standard divides water bodies into five classes according to utilization purposes and protection objectives, as described below:

Table 3.15 National environmental quality standards for surface water (MEP, 2002)

Grade	Description of water use
I	National nature conservation reserves; water source protection zones
II	Drinking water 1st Class; natural habitat for sensitive and rare aquatic species; fish and crustacean spawning; fish rearing
III	Drinking water 2nd Class (treatment required); sanctuaries for common aquatic species; fish survival in winter; fish migration; aquaculture; contact recreation
IV	Industrial use; active non-contact recreation

V	Industrial cooling only; agricultural irrigation; ordinary (low conservation value) landscape irrigation; passive recreation
VI	Not suitable for any purpose

	Item	Unit	Grade I	Grade II	Grade III	Grade IV	Grade V
1	Temperature		Man-made fluctuation of environmental water; temperature should be limited: maximum weekly; average temperature rise ≤ 1 °C, maximum weekly; average temperature drop.				
2	pH		6-9				
3	DO≥	mg/L	7.5	6	5	3	2
4	CODMn≤	mg/L	2	4	6	10	15
5	COD≤	mg/L	15	15	20	30	40
6	BOD5≤	mg/L	3	3	4	6	10
7	NH4	mg/L	0.15	0.5	1	1.5	2
8	TP≤	mg/L	0.02	0.1	0.2	0.3	0.4
9	TN≤	mg/L	0.2	0.5	1	1.5	2
10	Cu≤	mg/L	0.01	1	1	1	1
11	Zn≤	mg/L	0.05	1	1	2	2
12	F	mg/L	1	1	1	1.5	1.5
13	Se≤	mg/L	0.01	0.01	0.01	0.02	0.02
14	As≤	mg/L	0.05	0.05	0.05	0.1	0.1
15	Hg≤	mg/L	0.00005	0.00005	0.0001	0.001	0.001
16	Cd≤	mg/L	0.001	0.005	0.005	0.005	0.01
17	Pb≤	mg/L	0.01	0.01	0.05	0.05	0.1
18	Cr6+≤	mg/L	0.01	0.05	0.05	0.05	0.1
19	CN-≤	mg/L	0.005	0.005	0.2	0.2	0.2
20	V-phen≤	mg/L	0.002	0.002	0.005	0.01	0.1
21	Oils≤	mg/L	0.05	0.05	0.05	0.5	1
22	LAS≤	mg/L	0.2	0.2	0.2	0.2	0.3
23	S2-≤	mg/L	0.05	0.1	0.2	0.5	1
24	Fcg≤	cell/L	200	2,000	10,000	20,000	40,000

The standard GB 3838-2002 provides a fundamental framework for surface water quality regulation, monitoring and water quality assessment. There are 24 standard water quality parameters listed in GB3838-2002, arranged by three major categories and five sub-categories for chemical parameters. The grading of a surface water body's quality is done by assessing monthly measurements of the standard parameters. Each parameter is given five ranges of values that correspond to water use, Grades I–V, and there is a sixth grade for water that is unsuitable for use, Grade VI. The overall grade of a water sample is assigned referring to the worst grade of the analysed parameters. For the Yellow River, each sampling point represents a defined section of the river. A river reach can then be assessed in terms of the percentage of its length that falls within each grade. The river water quality indicator EP_2 is determined as the ratio of monitored river section with water quality no worse than national standard Grade III:

$$EP_{2,i} = \frac{GI_i}{L_i} \qquad (3.10)$$

where $EP_{2,i}$ is the score of Water Quality Indicator for the given year i, L_i is the total length of river section monitored and GI_i is the length of river section which achieved Grade III in the given year i.

According to YRCC, the Yellow River was maintained in healthy condition until 1980, when China’s economic growth took off. In 1980s, the annual wastewater discharged into the Yellow River was approximately 2.17 billion ton, this soon increased to 4.2 billion doubled in the early 1990s (Li, 2005). Facing emerging pressures of water quality degradation, government authorities started monitoring water quality on a regular basis in the 1990s. The data set we obtained starts from 1998, show that 29.2% of the river session monitored met the nation’s Grade III standard. The situation worsened in early 2000s, with a score of 0.19 for the year 2002, then gradually improved to 0.48 in 2010 (as seen in Figure 3.4). Worthy of mention, during the period from 1998 to 2010, the length of river been monitored (including mainstream and tributaries) increased from 7247 km to 14279 km. In addition, stringent regulation has been adopted, as the national standard for surface water monitoring has been updated with more indicators.

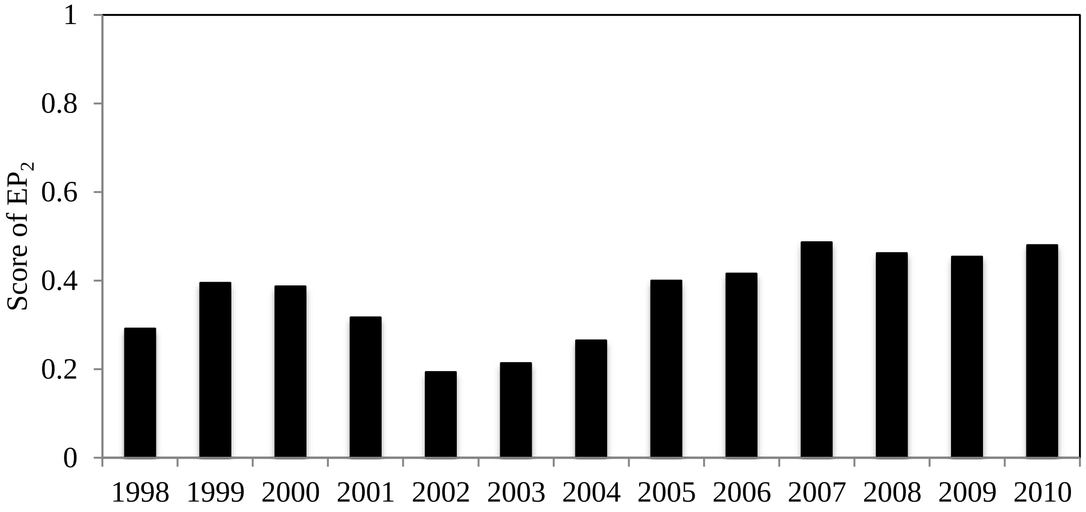


Figure 3.4 Water Quality Indicator for LYR

3.3.3 River Channel Capacity Indicator EP_3

The physical characteristics of a river system encompass fluvial geomorphological process and form, the interaction of sediment, flowing water, and organic factors to shape river channels and floodplains (Gippel et al., 2011). Together with hydrological processes and chemical processes for water self-purification, the geomorphological processes provide the template upon which ecological processes proceed. To support the sediment transport function of the Lower Yellow River, it is critical to maintain channel capacity in the main stream. There is also a benefit provided in alleviating flood risk by lowering riverbed level.

Commonly used indicators include annual sediment load and sediment concentration, bank stability, bed elevation, and channel capacity. Sediment transport is a very important function of LYR, therefore sediment load and concentration will be discussed separately in the sediment index. Bank stability will be discussed associated with the infrastructure index later in this chapter. Bed elevation indicates geographic and temporal variation but lack of consistency. In this research, channel capacity is selected as it best represents the flood discharge and sediment transport capacity of the Lower Yellow River (Liu, 2009). Figure 3.5 shows the linear relationship of bank-full runoff at different gauging stations in the Lower yellow River. The channel capacity at Huayuankou is used for calculating the river channel capacity indicator.

Based on previous researches on historical flood events since the 1950s, Yue (1996) proposed that the most efficient discharge was 3500 m^3/s at Huayuankou. Liu *et al.* (2006) further indicated that a flow lower than 4000 m^3/s at Huayuankou would be insufficient to support sediment transport through the entire reach of Lower Yellow River. The YRCC (2005) therefore suggests that the minimum value of bankfull channel capacity at Huayuankou should be 4000 m^3/s. According to Wu *et al.* (2008), the channel capacity at Huayuankou could reasonably be as high as 8000 m^3/s, and suggest a long-term expected capacity of 7000 m^3/s for sustainability.

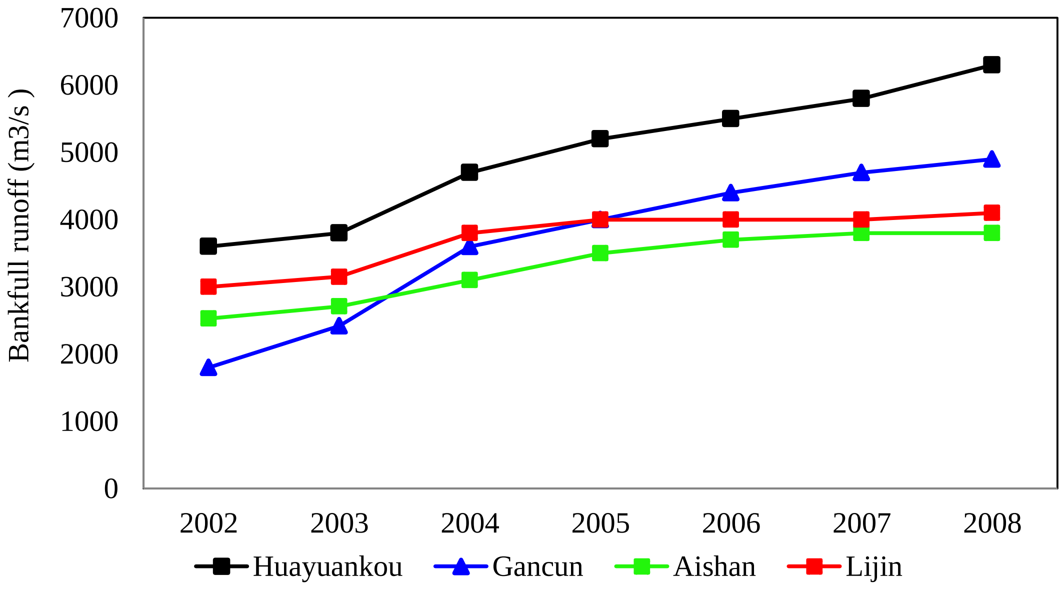


Figure 3.5 Channel capacity of the LYR since 2002

The River channel capacity Indicator is calculated as,

- If bankfull capacity at Huayuankou station (*C_i*) is greater than the long term expcted capacity of 7000 m^3/s, $EP_{3,i} = 1$ (3.11)
- If C_i is no greater than the minimum required capacity (4000 m^3/s),

  $$EP_{3,i} = 0 \qquad (3.12)$$
- If C_i falls between 4000 to 7000 m^3/s,

  $$EP_{3,i} = {(C_i - 4000)}\big/{3000} \qquad (3.13)$$

where $EP_{3,i}$ is the River Channel Capacity indictor score for the given year *i*, and C_i is the bankfull capacity of Huangkou of the given year *i*.

The results are presented in Figure 3.7. It shows that the river channel silted up in 1990s, which was mainly caused by water shortage and excessive sediment.

3.3.1 Sediment Transport Indicator EP_4

Sediment transport is a major function of many river courses. The Yellow River got its name from the excessive sediment it carries from Loess Plateau. The sediment transport function is critical to the Yellow River, because if this function is not satisfied, it is impossible for the river to meet its other functions (Ni and Liu, 2006).

Affected by grain roughness and bed roughness, sediment transport exists in two forms, namely, bed-load transport and suspended load transport. Sediment particles can be classified as sand ($d_{sand} > 62\mu m$), silt ($8 \le d_{silt} \le 62\mu m$) and clay ($d_{clay} \le 2\mu m$). For practical reasons, van Rijn (2007) assigns a clay and fine silt mixture to its own classification ($2 \le d_{cs} \le 8\mu m$). Bed-load transport is the transport of sediment particles within a thin layer above the bed, typically with a thickness of the order of 0.01m (Van and Leo, 2007). Suspended load is the transport of sediment particles above the bed-load layer, including wash load, which consists typically of clay-dominated fractions smaller than 8μm (Van and Leo, 2007) . Based on previous studies (Ni and Qian, 2002, Ni and Liu, 2006, Foster et al., 2008), the water-sediment nexus is determined by amount of water required for sediment transport, and the sediment transport efficiency will increase along with the increase in discharge. The sediment transport efficiency reaches a maximum value of 16.6 m^3/t, when the discharge reaches 3500 m^3/s.

Table 3.16 shows the temporal trends and regime shifts in runoff and sediment in the Yellow River. With the decade-average runoff halved over the past 50 years, the sediment loads show a significant decrease from an average of 16.83 10^8 t during the 1950s to 1.11 10^8 t during the 2000s.

Table 3.16 Runoff and sediment load at HYK station in different time periods

	Runoff (BCM)		Sediment (10^8 ton)	
Decade	Average	Coefficient of variation	Average	Coefficient of variation
1950-1959	48.74	20.18%	16.83	42.70%
1960-1969	50.59	38.03%	11.13	54.85%
1970-1979	38.16	23.45%	12.36	34.76%
1980-1989	41.18	29.05%	7.74	44.87%
1990-1999	25.78	23.57%	6.83	35.79%
2000-2008	23.21	19.57%	1.11	48.14%
Average	37.82	-	9.22	-

Figure 3.10 shows the large temporal and spatial variations in monthly sediment loads at different stations along the Yellow River. Sediment load in the Upper Yellow River (Toudaoguai station) is approximately 10% of that obtained in the Lower Yellow River over the same period of time. The maximum sediment load occurs at Huayuankou, with Lijin showing a similar trend. Therefore, the annual sediment discharge at Huayuankou Station is used herein to calculate the sediment transport indicator from:

$$EP_{4,i} = 1 - log_{10}(S_i + 1) / log_{10}\left(S_{max} + 1\right) \qquad (3.14)$$

where S_i is the total sediment discharge at Huayuankou Station in the year i, and S_{max} is the maximum annual sediment load for the period of 1960 to 2010.

The results are presented in Figure 3.9. It shows a gradual improvement in the sediment indicator. A significant reduction in sediment load has been identified, owing to efforts on forestation and sediment control in the Losses Plateau.

3.3.1 Biodiversity Indicator EP_5

The biodiversity of the lower Yellow River is based on assessment of fish, and riparian plants and macro invertebrates. 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. 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 bank full discharge. Globally, stream macro-invertebrates are probably one of the most commonly used biological measures of stream health. For example, in Europe there are more than one hundred different bio-assessment methods in use, and two-thirds of these methods are based on macro invertebrates.

A comprehensive ecological survey for LYR was conducted by the China Academy of Science in 2008 (see Table 3.17). Table 3.18 compares the main ecological indicators in 1980 and 2008.

Table 3.17 Ecological survey of Lower Yellow River 2008 (Gippel et al., 2011)

Survey Location	Observed				Expected			
Survey items	HYK	GC	LJ	Delta	HYK	GC	LJ	Delta
Number of Fish species	31	12	6	17	83	83	83	108
Number of Riparian plants species	66	69	53	35	149	149	149	193
Number of species	28	12	5	2	35	17	17	69
Macro invertebrates Density (individuals/m^2)	432	110	287	320	700	400	400	1050

Table 3.18 Comparison of ecological surveys in 1998 and 2008 (YRIHR, 2010)

Category	Phytoplankton		Zooplankton		Fish
Year	Number of species	Biomass (mg/l)	Number of species	Biomass (mg/l)	Number of species
1980	197	0.411	24	2.44	125
2008	157	1.135	67	0.587	54

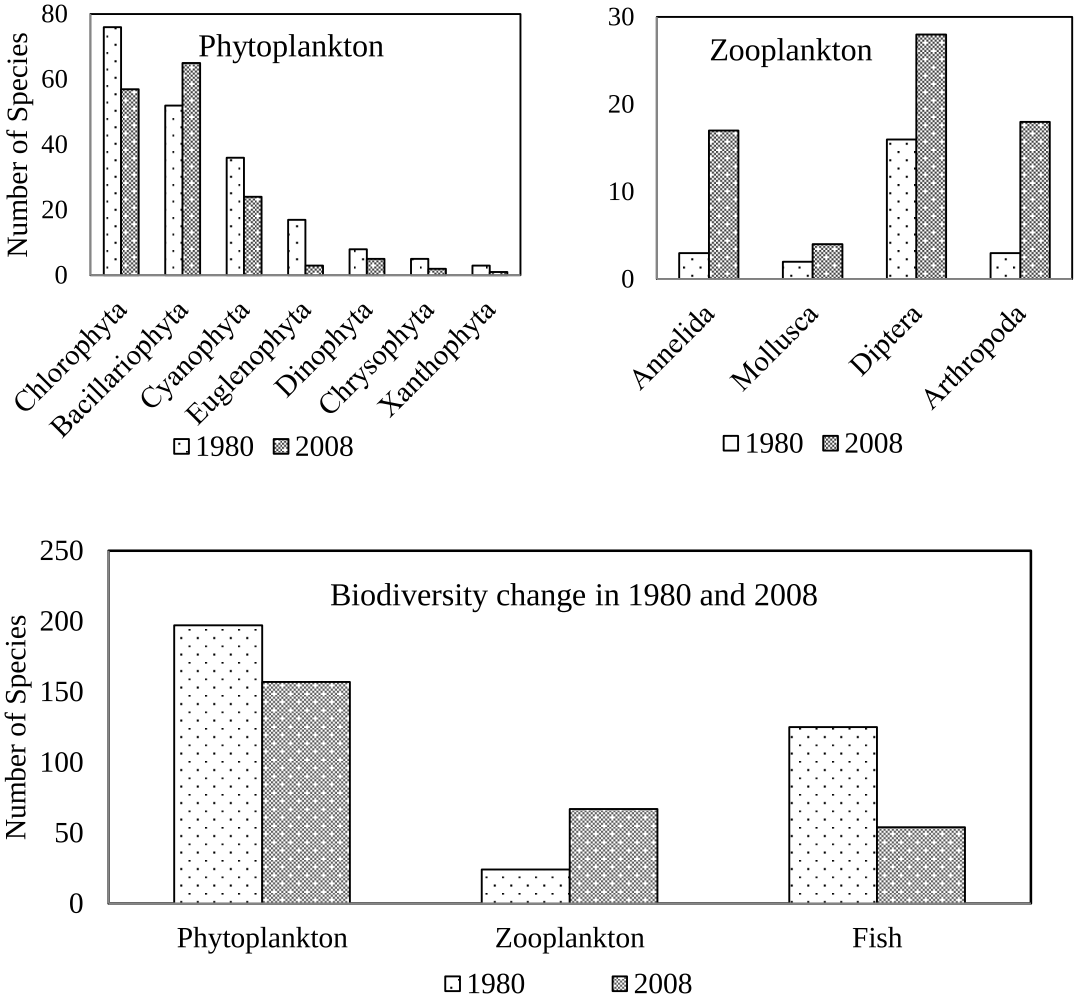


Figure 3.6 Biodiversity change in LYR in 1980 and 2008

The Biodiversity Indicator is calculated by,

$$EP_{5,i} = \frac{N_{obs}}{N_{exp}} \tag{3.15}$$

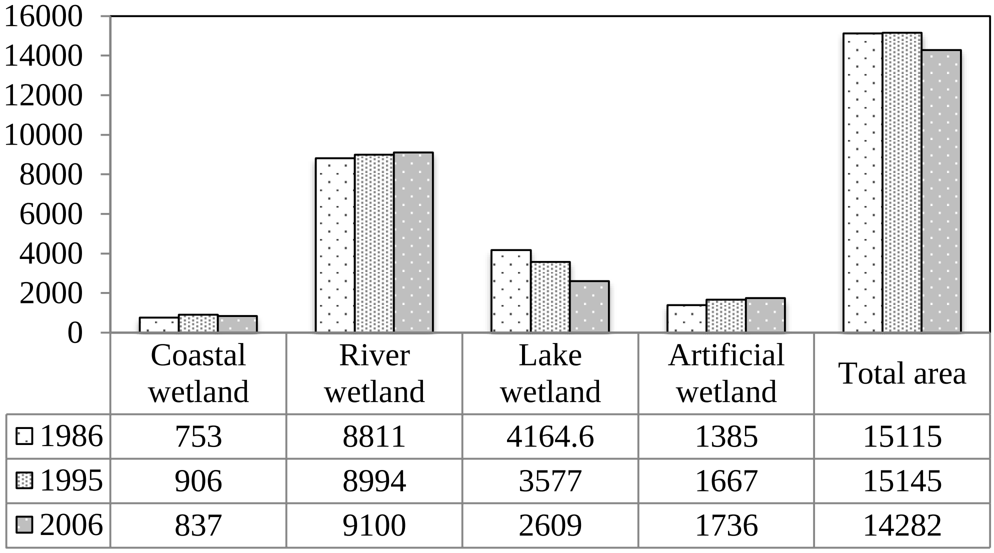
where N_{obs} is the number of species observed in the ecological survey, and N_{exp} is the number of species expected, with reference to China Academy of Science (YRIHR and CAS, 2009).

According to the calculation, for the year 2008 the biodiversity scores for Huayuankou, Gaocun, Lijin and the Yellow River Delta are 0.56, 0.40, 0.36, and 0.17

respectively. The integrated biodiversity score for LYR in 2008 is the mean of the scores at four different locations, 0.37. And the biodiversity score for the year 1980 is 0.63. According to YRCC, the biodiversity status of LYR is considered to be in a sustainable, healthy condition during the 1950s. It is therefore set as the sustainable benchmark, and a score of 1 is given for 1950.

3.3.2 Land Use Indicator EP_6

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 due, to a large extent, to the unusually rapid rate of 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.



	Coastal wetland	River wetland	Lake wetland	Artificial wetland	Total area
□1986	753	8811	4164.6	1385	15115
▨1995	906	8994	3577	1667	15145
■2006	837	9100	2609	1736	14282

Figure 3.7 Wetland change in LYR by category (km^2) (YRIHR and CAS, 2009)

The land use indicator is determined by the percentage of change in natural wetland areas in the given year, comparing to the base year. Natural wetland includes coastal wetland, river wetland, and lake wetland. Although artificial wetland plays an important role in terms of water conservation and ecosystem recovery, the loss of natural wetland is irreversible and cannot be offset by developing artificial wetland. Through stakeholder interview (Zhang, pers comm., 2011). It has been observed that there is little degradation of wetland in the 1980s and the flood plain has been maintained to a sustainable level. Therefore, 1986 is considered as the benchmark (score 1). Also, it is generally believed that over a third of natural wetland loss will be critical (Yao, pers comm., 2011) and so unsustainable (score 0). Scores for year 1995 and 2006 are calculated by rescaling, and are 0.96 and 0.82 respectively.

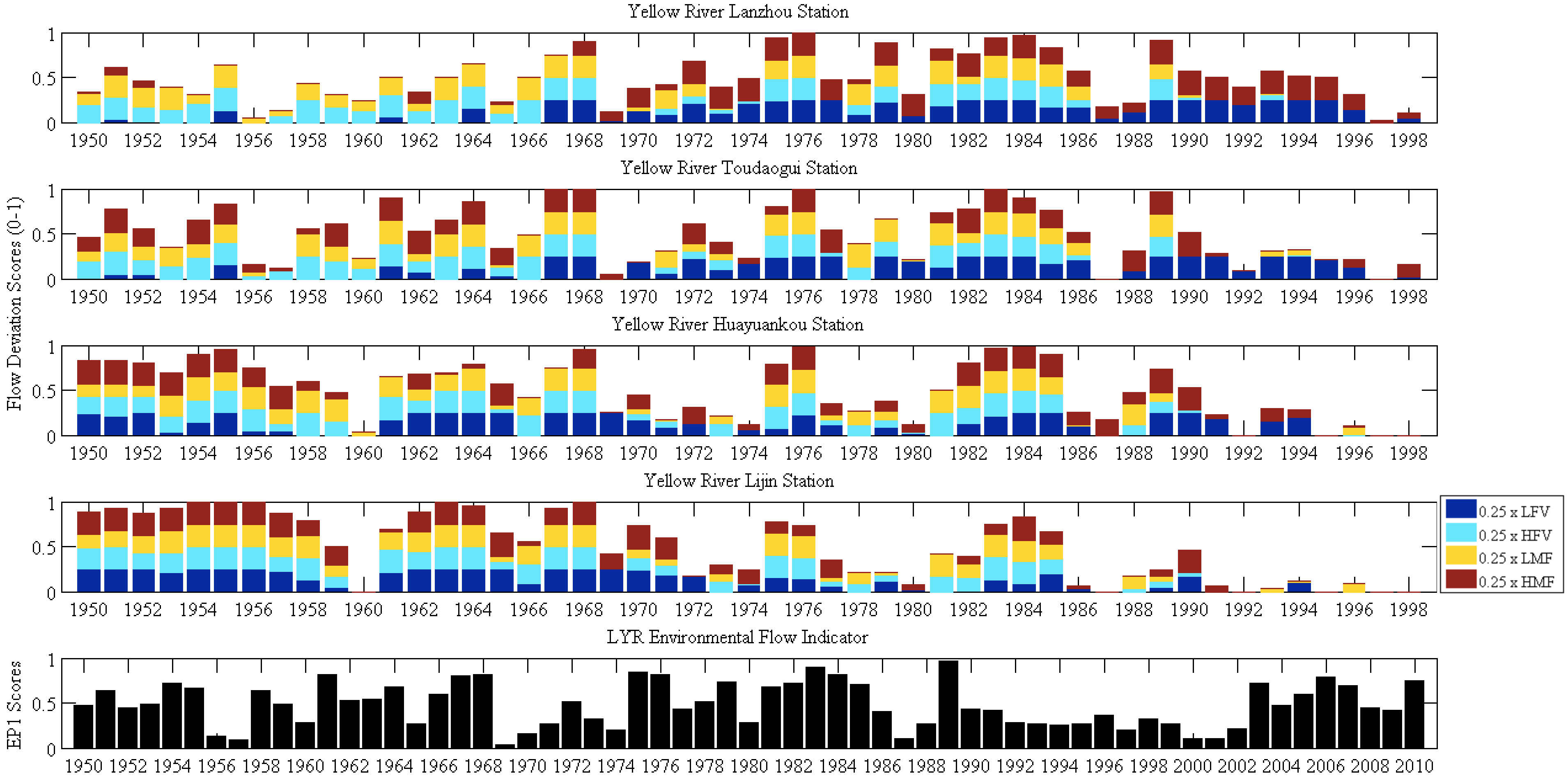


Figure 3.8 Environmental Flow Indicator of LYR

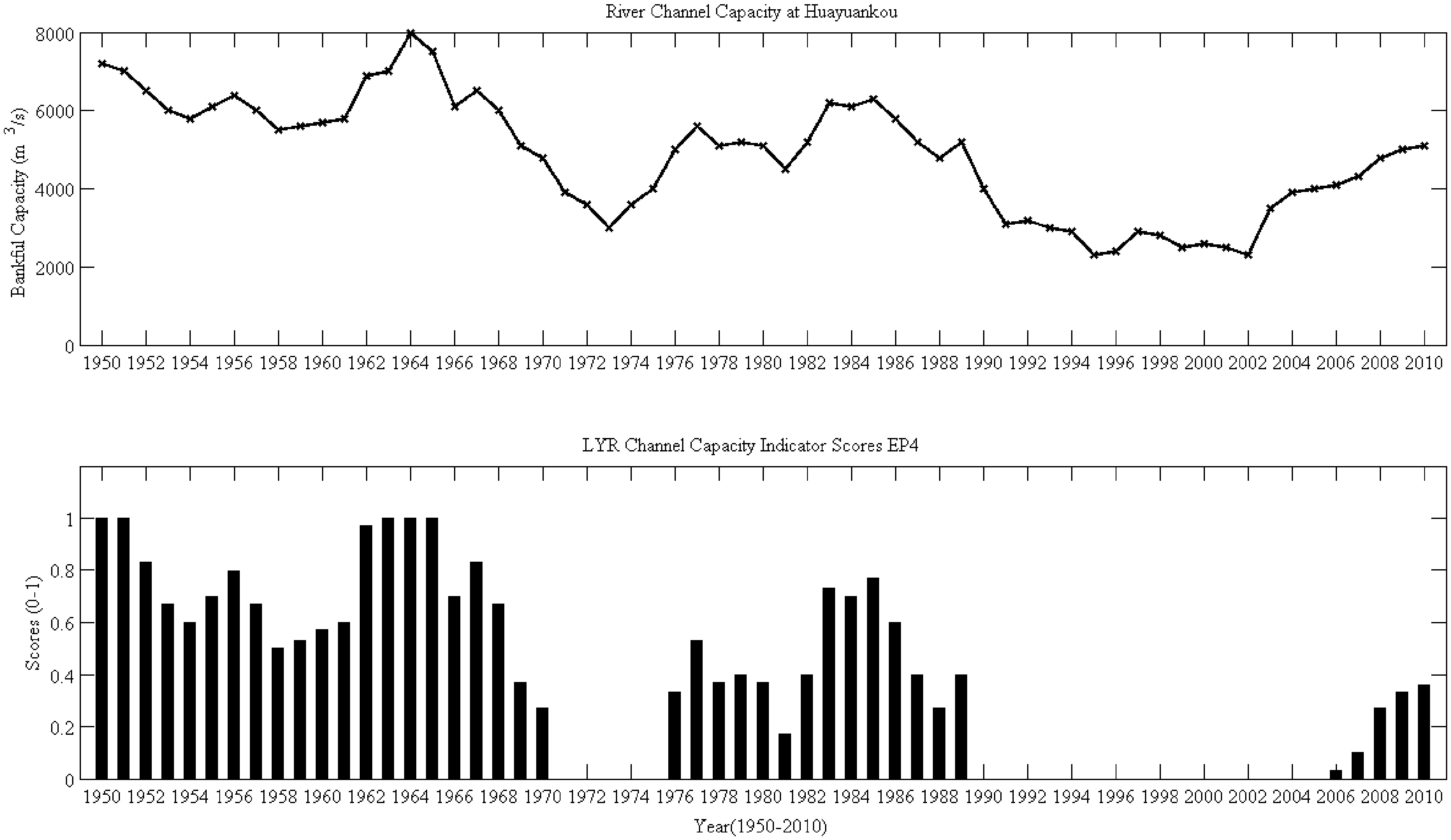


Figure 3.9 River Channel Capacity of LYR

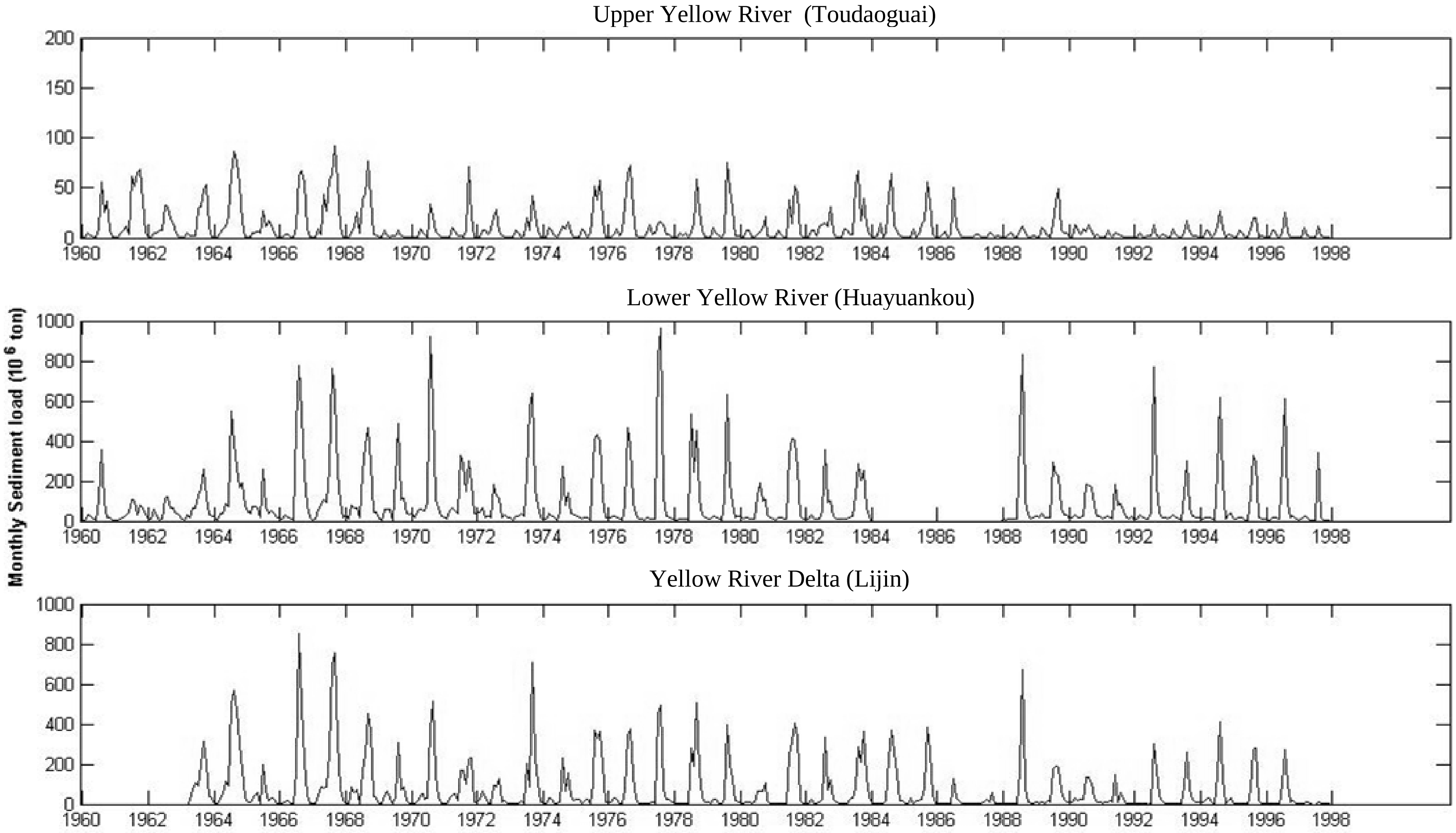


Figure 3.10 Monthly sediment load at different stations of the Yellow River

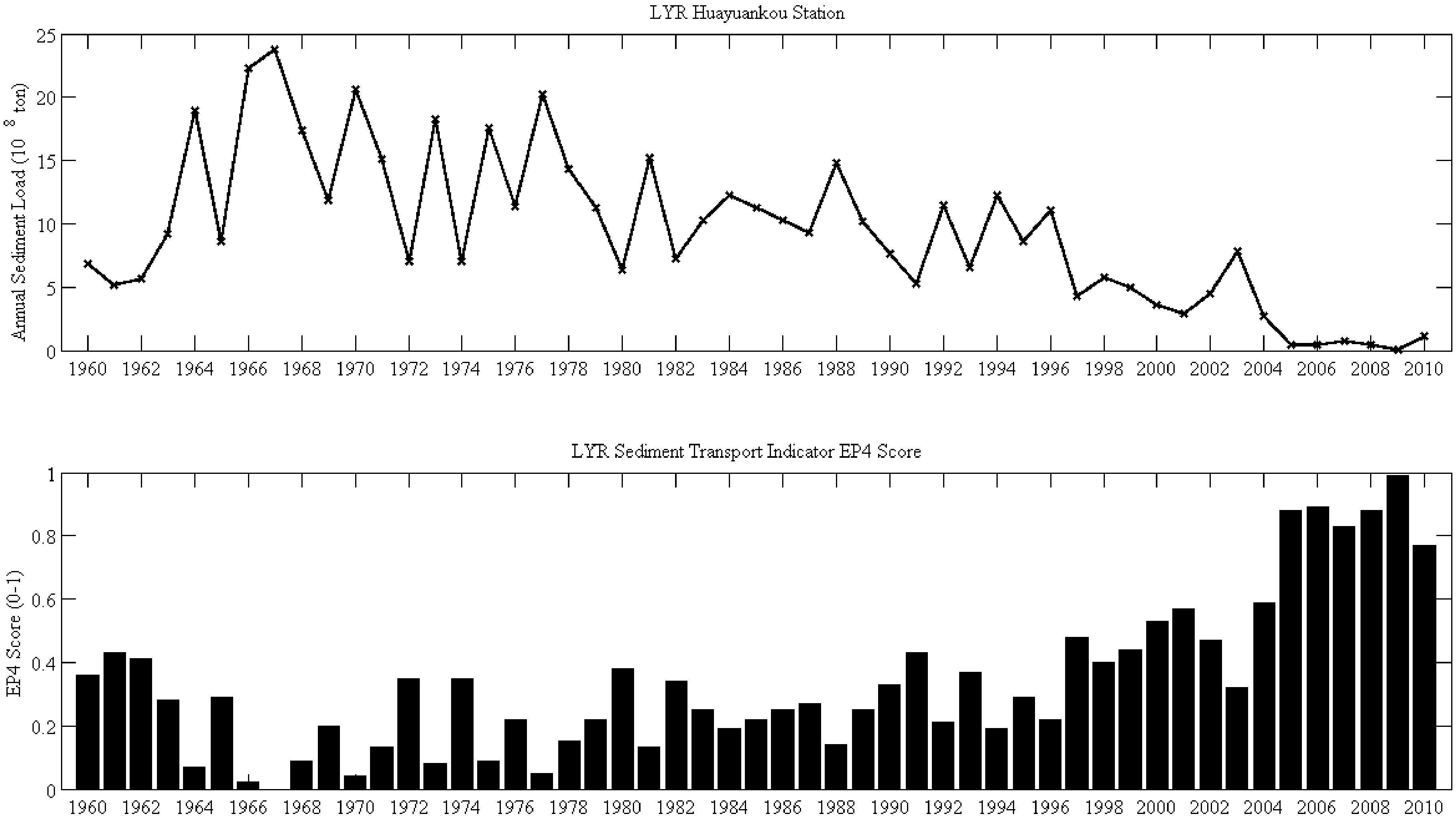


Figure 3.11 Sediment Transport Indicator of LYR

3.4 Social Wellbeing of LYR

3.4.1 Flood Risk Indicator SW_1

Floods occur when the river discharge exceeds the capacity of the channel, and water overflows onto surrounding areas. Through mechanisms such as surface water transfer and groundwater seepage, a river and its floodplain have the ability to regulate hydrological processes and delay flood effects. Flood discharge capacity is a function of longitudinal and cross-sectional channel shape, which collectively contribute to bankfull discharge capacity (Ni and Liu, 2006). Figure 3.12 shows the significant temporal and spatial variations in river channel bank-full capacity (Q_{BF}) at Huayuankou. When the river discharge exceeds the bankfull discharge, the floodplain is inundated, posing a socio-economic threat to local communities. Human activities often intensify the impacts of floods by developing infrastructures on flood plains. In the Lower yellow River, there are over 3 million people settled in floodplains, these people are most vulnerable to flood risks.

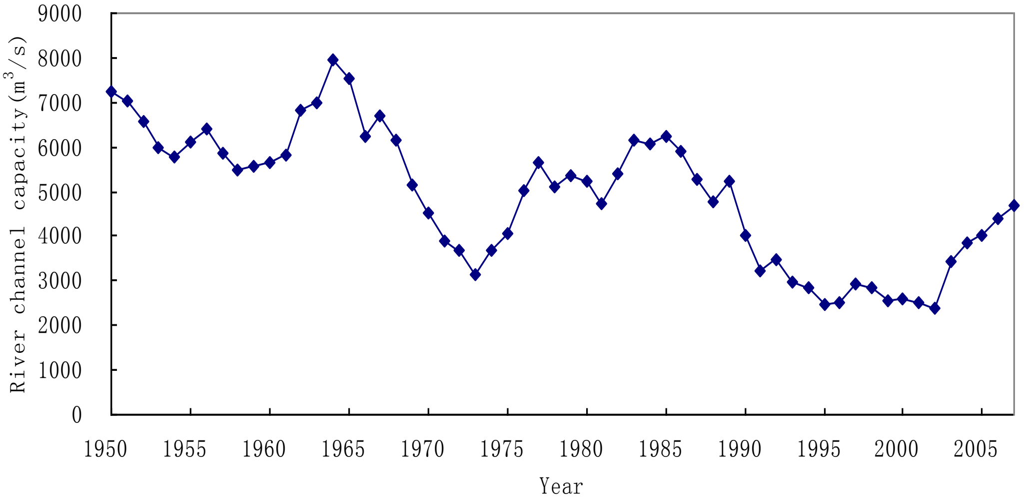


Figure 3.12 River channel capacity at Huayuankou since 1950 (Jiang, 2011)

The flood risk index incorporates by two sub-indicators, the flood frequency indicator, and the flood volume indicator. The flood frequency sub-indicator (FF) is calculated by the number of days (N_i) when daily discharge exceeds bankfull discharge capacity (Q_{BF}). The flood volume sub-indicator (FV) is calculated by using a peaks-over-threshold (POT) method. POT defines V_i as the total flood volume in year i when the daily discharge Q is above the bank-full discharge Q_{BF}. Standard scores for FF and FV are calculated as below. Please note that a square is applied to rescale the indicator score values. The results were compared with historical flood records ,

$$FF_i = \left(1 - \frac{N_i}{N_{max}}\right)^2 \tag{3.16}$$

$$FV_i = \left(1 - \frac{V_i}{V_{max}}\right)^2 \tag{3.17}$$

Equal weighting is given to the two sub-indicators, FF and FV. The Flood Risk Index $(SW_{1,i})$ is calculated as below,

$$SW_{1,i} = 0.5 \times \left(FF_i + FV_i\right) \qquad (3.18)$$

where $SW_{1,i}$ is the flood risk indicator score for the given year i; N_i is the number of days when the daily discharge exceeds Q_{BF} in year i; N_{max} is the maximum value of N_i during year 1950 to 1997; V_i is the cumulative flood volume when daily discharge exceeds Q_{BF} in year I; V_{max} is the maximum value of V_i from1950 to 1997.

Due to data scarcity, annual discharge at Huayuankou is used as a surrogate that determines the flood risk indicator during 1998 to 2010. The score is calculated by categorical scales, according to the percentiles of the distribution of the data set:

If $D_i \geq D_1, SW_{1,i} = 0,$

if $D_1 \geq D_i > D_5, SW_{1,i} = 0.2,$

if $D_5 \geq D_i > D_{25}, SW_{1,i} = 0.4$,

if $D_{25} \geq D_i > D_{50}, SW_{1,i} = 0.5$,

if $D_{50} \geq D_i > D_{75}, SW_{1,i} = 0.6$,

if $D_{75} \geq D_i > D_{85}, SW_{1,i} = 0.8$,

if $D_{85} \geq D_i > D_{100}, SW_{1,i} = 1.0$ (3.19)

where D_i is the annual discharge at Huayuankou in year i; D_k is the upper k^{th} percentile of annual discharge at Huayuankou during year 1950 to 2010; and $0 < \mathrm{k} \leq 100$.

The results of the flood risk indicator are presented in Figure 3.13. It shows large variations over time, in response to uncertainty in climate. It is noted that LYR has been experiencing droughts more frequently in the recent twenty years, however, it is still important to improve resilience to potential floods in the context of climate change.

3.4.2 Drought Risk Indicator SW_2

The Yellow River Basin has been facing serious drought risk given the continuous decrease in average annual discharge over recent decades (see Table 3.16). For example, the river ceased to flow at Lijin Station near the Yellow River estuary for 221 days in 1997 (Figure 3.13). No-flow events occur when there is zero-discharge in the Yellow River. Functional no-flow events refer to cases when there is insufficient runoff to meet the minimum water demand of the main river functions (Ni and Qian, 2002).

There are inherent differences between these two norms: a no-flow event occurs when the river ceases to flow; a functional no-flow event is when the flow rate is so low that major river functions are interrupted. Impacts of functional no-flow events are related to spatial and temporal variations, frequency of low flows and the vulnerability. Ni and Qian (2002) advance the concept by identifying functional no-flow thresholds for different locations at Lower Yellow River (Table 3.19).

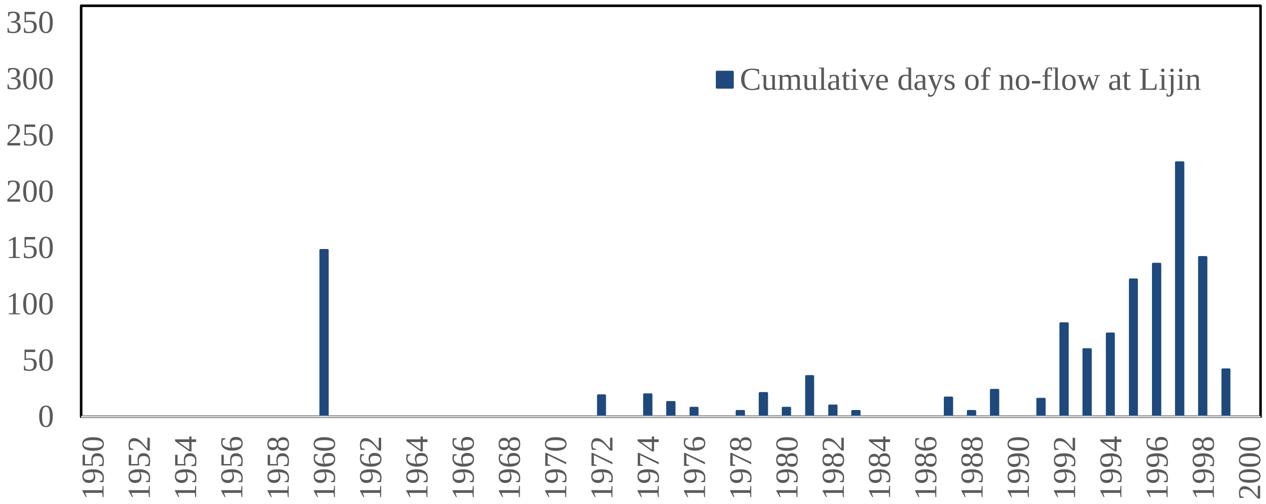


Figure 3.13 Number of no-flow days at Lijin (Jiang, 2011)

Table 3.19 Functional no flow thresholds for Lower Yellow River (Ni and Qian, 2002)

Gauging Station	*Minimum Environmental Flow* (m^3/s)	*Annual Runoff* ($10^9\ m^3$)
Huayuankou	231.5	25.3-26.0
Gaocun	234.3	28.9-32.7
Aishan	158.0	26.0-30.6

Drought Risk Indicator is determined by the number of functional no-flow days in the Lower Yellow River. Three different locations are considered, namely, Huayuankou, Gaocun, and Aishan. The standard score of SW_2 is calculated as below,

$$SW_{2,i} = \frac{1}{3} \times \left[\left(1 - \frac{N_{hyk,i}}{N_{hyk,max}}\right)^2 + \left(1 - \frac{N_{gc,i}}{N_{gc,max}}\right)^2 + \left(1 - \frac{N_{as,i}}{N_{as,max}}\right)^2 \right] \qquad (3.20)$$

where N_i is the number of days when the daily discharge is lower than the functional no flow threshold in year i, and hyk, gc, and as refers to Huayuankou, Gaocun and Aishan stations respectively; and N_{max} is the maximum number of days when the discharge is lower than the threshold identified during year 1950 to 2010.

The results presented in Figure 3.15 show that LYR suffered serious droughts between 1985 to 1990. This is mainly due to insufficient water resource, increasing demanding, and excessive abstraction. The condition improved significantly since 2000, as YRCC underpinned its water allocation policy (discussed in section 3.5.5) in 1997, further developed extensive infrastructures to regulate flow and sediment (see section 3.6.1).

3.4.3 Water Consumption Indicator SW_3

The water consumption indicator is determined by total volume of annual water withdrawal for human consumption. According to the YRCC, annual water consumption sharply increased from 12.2 10^9 m^3 in 1950 to 29.9 10^9 m^3 in 1990. Water consumption data are collected from different sources: the decadal water consumption rate from 1950s and 1990s (see Table 3.20) is calculated by analysing environmental flows and human activities in the river basin Zhang, Liu and Li (2004)., Herein the annual water consumption data are obtained from the YRCC annual bulletins from 1998 to 2010.

Table 3.20 Estimated average total water consumption (Zhang *et al.* 2004)

Year	1950-55	1956-59	1960s	1970s	1980s	1990s
Consumption (10^9 m^3)	12.20	18.05	17.63	24.92	29.92	29.42

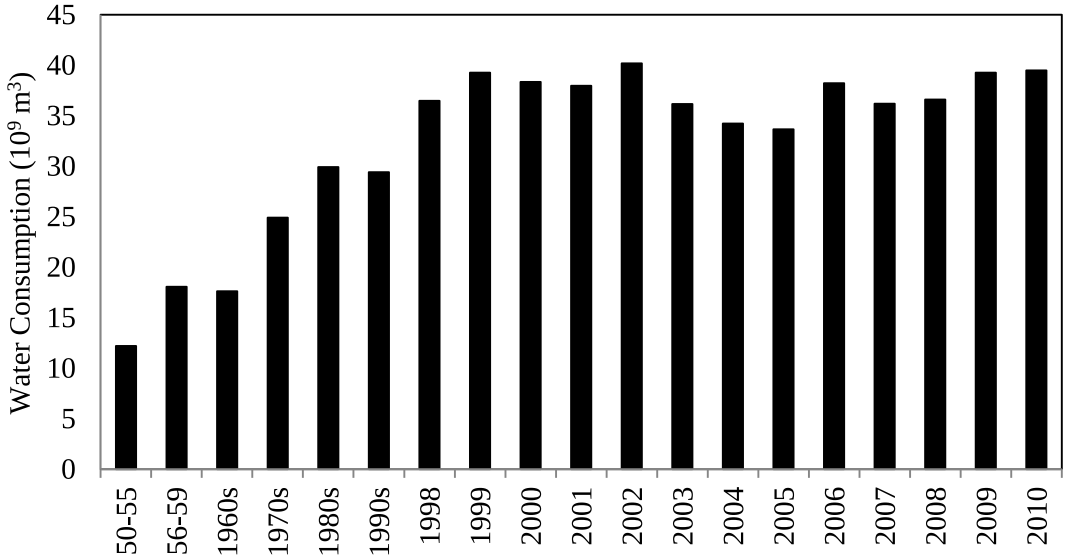


Figure 3.14 Water consumption statistics for the Yellow River Basin (Zhang *et al.* 2004, YRCC 2011)

The water consumption indicator scores are calculated by rescaling as,

$$SW_{3,i} = 1 - \frac{C_i - C_{min}}{C_{max} - C_{min}} \qquad (3.21)$$

where C_i is the total water consumption in the Yellow River Basin in year i, C_{max} and C_{min} are the maximum and minimum values of total water consumption during the period from 1950 to 2010 respectively.

The final results are presented in Figure 3.19, showing continuous decline in the water consumption indicator in the later half of the 20th century, due to increasing water demand for socioeconomic development. The indicator stabilizes after 2000, when YRCC strengthened regulation on water abstraction. Improvements are identified in some years (2003, 2004 and 2007).

3.4.4 Water Access Indicator SW_4

A primary function of most major rivers is to provide water resources to help sustain agriculture, industry, and municipalities; i.e. to fulfil a socioeconomic function. Ni and Liu (2007) proposed that water quality, water quantity, and percentage of time when demand is satisfied (typically 95% for the LYR) are the important factors for the water supply function. Renewable water resources and water quality have been examined under the environmental performance domain. This indicator focuses on access to public water supply, which is fundamental to social wellbeing.

Figure 3.15 Water supply access sub-indicator

Due to unavailability of regional data, the national rate of water supply asscess is used as a surrogate. It is assumed that provinces in LYR experience a similar trend to the nationalwide development of water supply utilities. And the score for the water access indicator is calculated by rescaling,

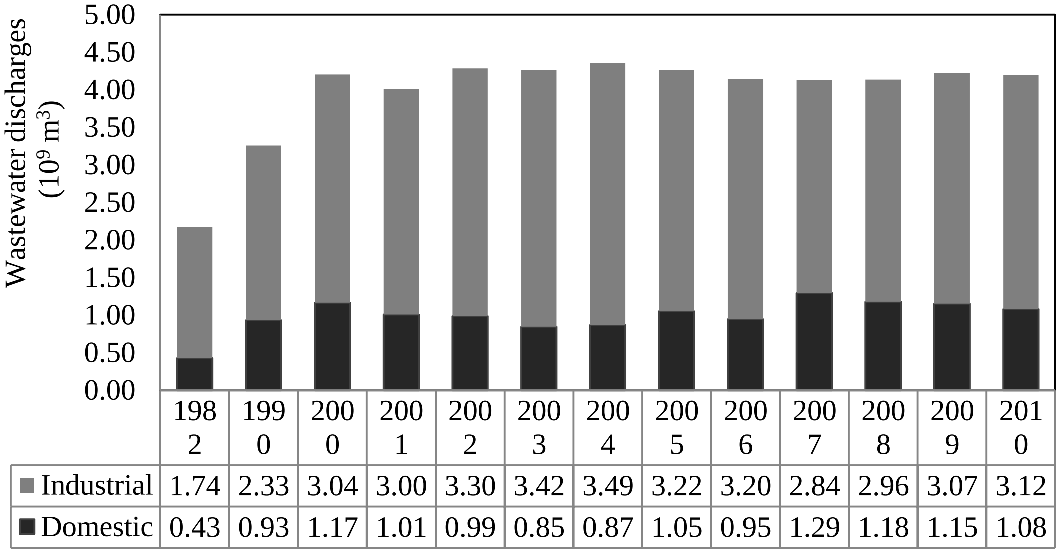
$$SW_{4,i} = \frac{A_i}{A_{max}} \tag{3.22}$$

where $SW_{4,i}$ is the indicator score for the given year i; A_i refers to access to water supply access in the year i; A_{max} is the maxmium acess rate to water supply from 1949 to 2010 (as 98% for the year of 2010).

The final results of the Water Access Indicator are presented in Figure 3.20. It indicates great achievement in water supply utilities in China, with almost 100% access to public water supply in 2010.

3.4.5 Wastewater Discharge Indicator SW_5

Wastewater discharge indicator is determined by the total volume of wastewater discharged to the LYR, including wastewater from point source i.e. domestic wastewater, and industrial wastewater, and non-point source i.e. agriculture. Figure 3.16 presents the data obtained for the years1982, 1990, and 2000 to 2010.



	1982	1990	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
▨ Industrial	1.74	2.33	3.04	3.00	3.30	3.42	3.49	3.22	3.20	2.84	2.96	3.07	3.12
■ Domestic	0.43	0.93	1.17	1.01	0.99	0.85	0.87	1.05	0.95	1.29	1.18	1.15	1.08

Figure 3.16 Wastewater discharges in the Yellow River Basin

Scores for SW_5 are calculated by rescaling the dataset,

$$SW_{5,i} = 1 - \frac{D_i - D_{max}}{D_{max} - D_{min}} \tag{3.23}$$

where $SW_{5,i}$ is the indicator score and D_i is the total amount of wastewater discharged for the given year i; and D_{max} and D_{min} are the maximum and minimum values of total wastewater discharged in the Yellow River Basin during 1980 to 2010 respectively.

And the final results are presented in Figure 3.21. It shows a positive correlation with the water consumption indicator: the more water consumed, more wastewater discharged into the river.

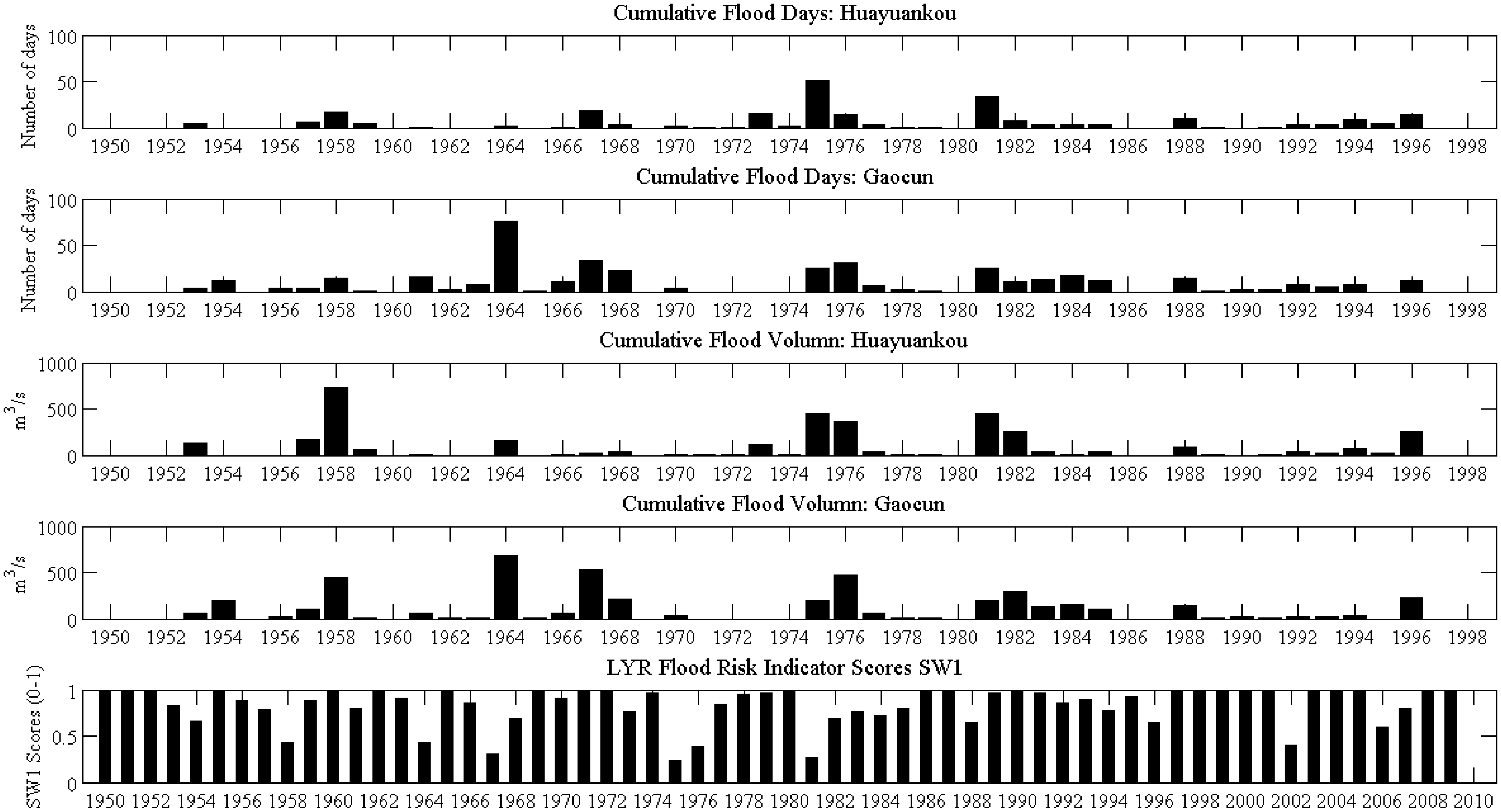
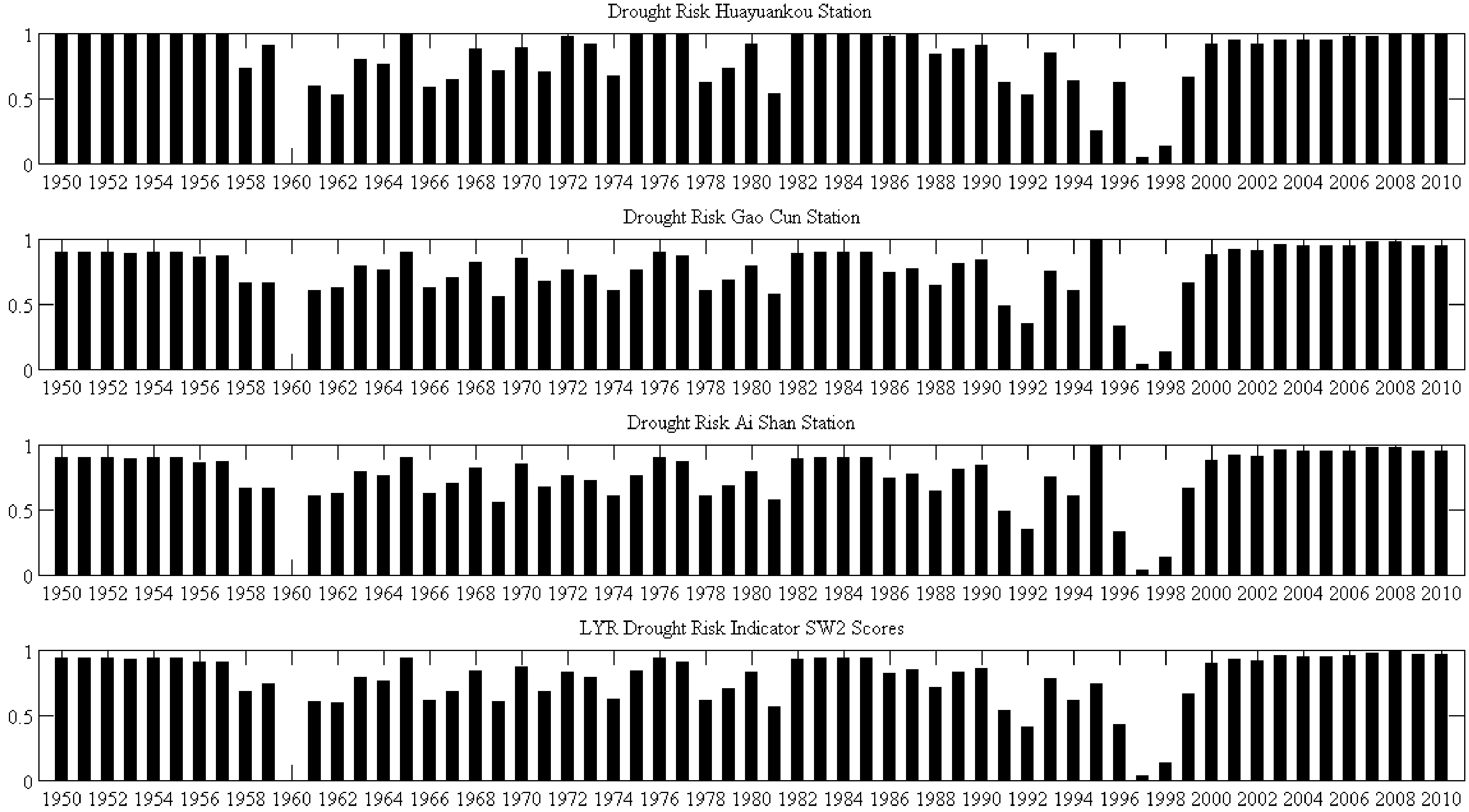


Figure 3.17 Flood Risk Indicator of LYR


Drought Risk Huayuankou Station

Drought Risk Gao Cun Station

Drought Risk Ai Shan Station

LYR Drought Risk Indicator SW2 Scores

Figure 3.18 Drought Risk Indicator of LYR

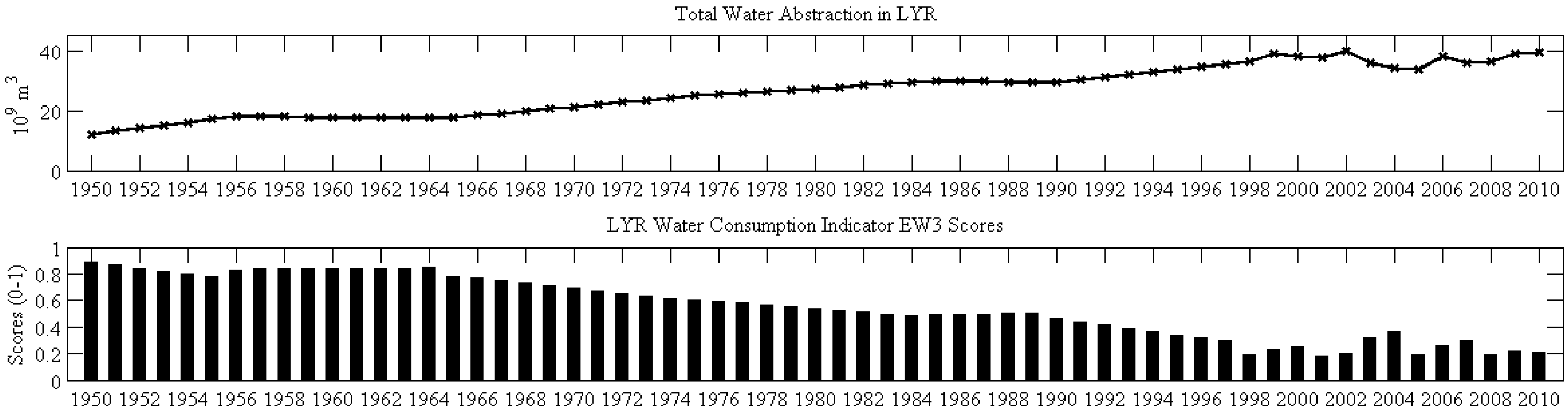


Figure 3.19 Annual Water Abstraction and the Water Consumption Indicator of LYR

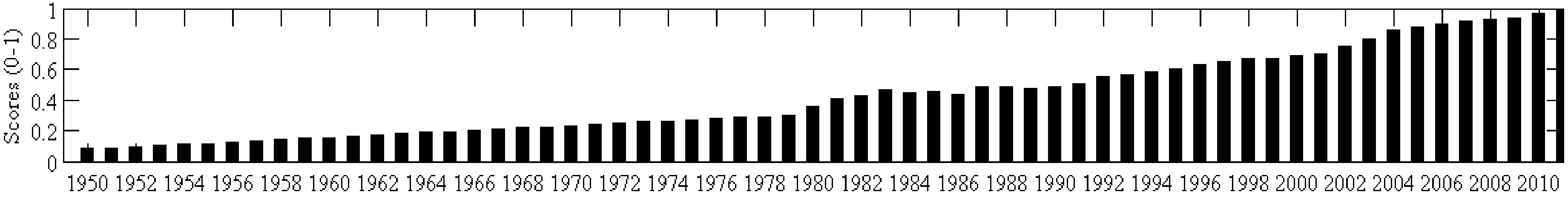


Figure 3.20 Water Access Indicator of LYR

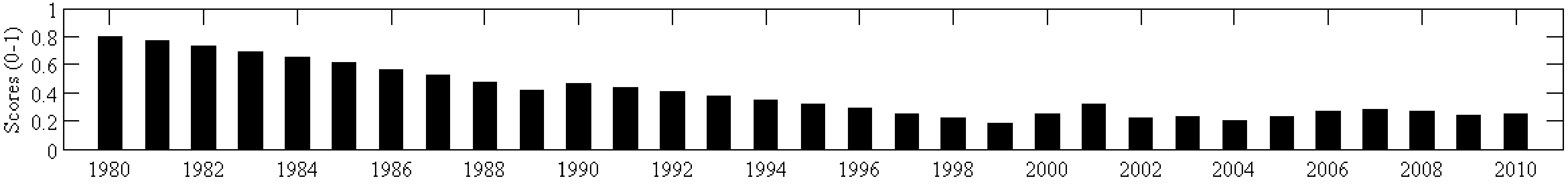


Figure 3.21 Wastewater Discharge Indicator of LYR

3.4.6 Water Allocation Indicator SW_6

As economic development in China has accelerated over the past twenty years, disputes have intensified over the Yellow River's. An inter-provincial water allocation plan was established by the State Council in 1987. Based on an annual available resource of 58 billion cubic meters (BCM) of water, 21 BCM were designated for the environmental flow, whilst the remaining 37 BCM were allocated to 9 provinces respectively (as seen in Table 3.21). However, the actual available water resources barely reached 58 BCM in 1990s. Implementation of the 1987 allocation resulted in an average annual discharge of 17 BCM in the first six years after 1990 (Liang, 2005), which was insufficient to maintain minimum environmental flow. In 1998, the State Council revised the 1987 water allocation scheme and reduced the quotas by a fixed proportion during drought years, with decreases evenly divided among provinces. This aimed to maintain consistent environmental flow for major river functions.

Compared with the Upper and Middle reaches, the Lower Yellow River has more often approached or exceeded its quota for water withdrawal.
Figure 3.22 compares the water allocation plan with actual water withdrawal by different sections of the river. This intensified water scarcity in LYR especially in dry years. In 1997, the river ceased to flow at several sections for over 200 days in Shandong Province. LYR provinces therefore claimed an extra quota of water to support regional development, and 0.8 BCM extra water was allocated in the year 2004. However, this created conflicts concerning fairness and water rights among different regions. In response, certain provinces appealed to central government to

establish a water withdrawal permits trading system, regulated by an economic instrument.

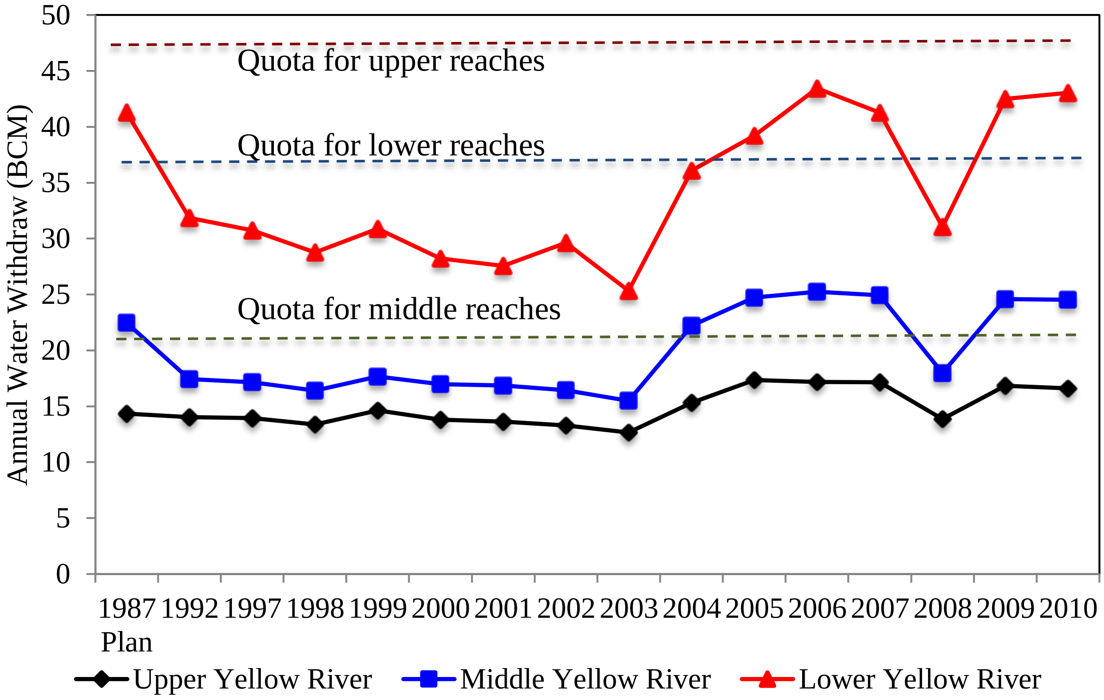


Figure 3.22 The 1987 Water Allocation Plan and actual water withdrawal for different sections of the Yellow River (YRIHR and CAS, 2009)

Despite inter-provincial conflicts, the Water Allocation Indicator in this research focuses on the tradeoff between the water resources for ecosystem and human uses. The Water Allocation Indicator indicates the extent to which the environmental flow is sufficient to the support river ecosystem. The amount of environmental flow achieved according to the 1987 Yellow River Allocation Plan is listed in Table 3.21. The indicator score is calculated as,

$$\text{If } V_i \geq V_{exp}\text{ , } SW_{6,i} = 1 \qquad (3.24)$$

If $V_i < V_{exp}$,

$$SW_{6,i} = {V_i}/{V_{exp}} \qquad (3.25)$$

where V_i is the environmental flow volume of the given year i; V_{exp} is the expected environmental flow volume as according to the 1987 Allocation Plan, which is 21 BCM.

The final results are presented in Figure 3.23. It reveals the competing demands for water between the environment and human activities. The goals in the 1987 Water Allocation Plans are particular difficult to achieve in drought years, such as 1997, 2002 and 2006.

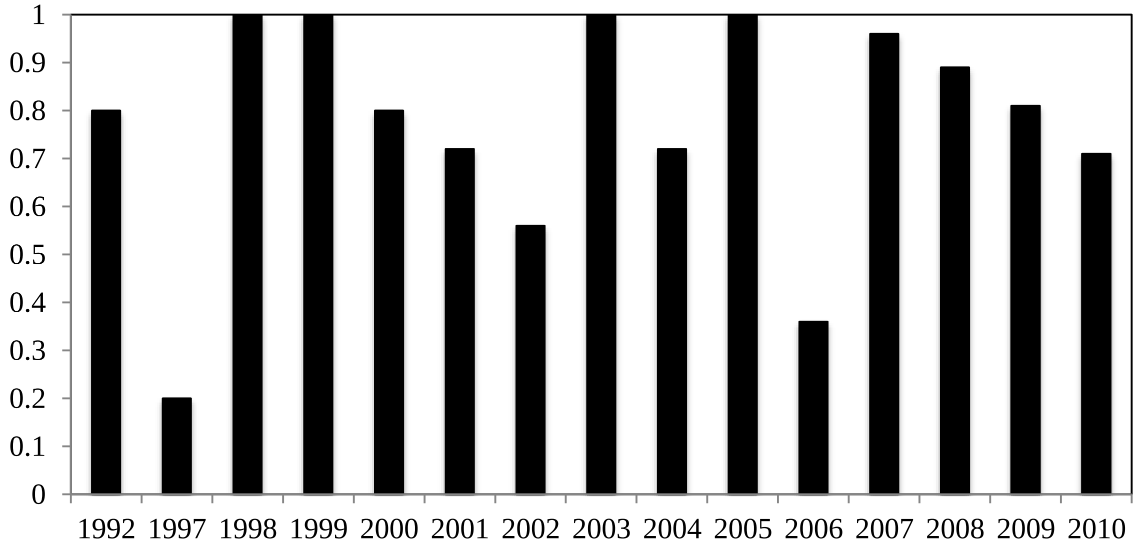


Figure 3.23 Water Allocation Indicator of LYR

Table 3.21 Water allocation among provinces in the Yellow River Basin

Province	1987 Water Allocation Plan	Actual annual withdrawal (BCM)														
		1992	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Qinghai	*1.41*	1.58	1.23	1.16	1.21	1.32	1.13	1.17	1.09	1.25	1.25	1.54	1.45	1.21	1.25	1.21
Sichuan	*0.04*	0.00	0.07	0.01	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03
Gansu	*3.04*	2.45	2.58	2.35	2.58	2.74	2.69	2.61	2.92	2.41	3.34	3.43	3.51	3.01	3.39	3.43
Ningxia	*4.00*	3.37	3.95	3.71	4.15	3.78	3.70	3.57	3.56	4.05	4.46	4.14	4.20	3.90	4.08	3.85
Inner Mongolia	*5.86*	6.62	6.12	6.15	6.65	5.95	6.10	5.92	5.05	7.59	8.26	8.06	7.96	5.71	8.10	8.10
Shaanxi	*3.80*	1.32	1.97	1.97	2.09	2.18	2.18	2.11	1.87	4.04	4.34	4.78	4.52	2.68	4.52	4.39
Shanxi	*4.31*	2.10	1.22	1.05	0.96	0.99	1.05	1.04	0.96	2.85	3.04	3.29	3.28	1.45	3.22	3.53
Henan	*5.54*	3.38	3.67	2.95	3.46	3.15	2.94	3.60	2.83	4.53	4.88	5.78	5.03	3.94	5.78	5.82
Shandong	*7.00*	8.93	8.70	8.36	8.47	6.39	6.34	8.03	5.06	5.67	6.44	8.82	7.83	6.97	8.03	8.13
Hebei & Tianjin	*2.00*	0.00	0.00	0.00	0.32	0.72	0.36	0.51	1.01	0.81	0.13	0.30	0.19	0.73	0.87	1.02
Total withdrawn	*37.00*	29.75	29.51	27.71	29.92	27.24	26.51	28.58	24.38	33.23	36.17	40.16	37.99	29.62	39.27	39.51
Enviro-Flow	*21.00*	16.78	4.13	27.24	26.36	16.90	15.14	11.72	44.03	15.04	27.13	7.63	20.18	18.75	17.07	14.89
Total Runoff	*58.00*	52.13	34.63	54.95	56.28	44.14	41.65	40.30	68.41	48.27	63.30	47.79	58.17	48.37	56.34	54.40
Score		0.80	0.20	1.00	1.00	0.80	0.72	0.56	1.00	0.72	1.00	0.36	0.96	0.89	0.81	0.71

3.4.7 Public Health Indicator SW_7

Water has a profound influence on public health. Priorities have been given to ensure access to safe drinking water and hygienic sanitation, minimize risks of flooding and drought. The Public Health Indicator here specifically focuses on people affected by water-borne disease and water contamination events. Poor microbiological quality is a major cause of infectious water-related disease outbreaks, which could further lead to serious epidemics (WHO, 2008). Additionally, it is known that chemical contamination can result from industrial development and untreated discharge of wastewater, with potential chronic long-term effects.

Table 3.22 lists the number of water contamination events reported in LYR. It can be seen that their occurrence reduces with time. Due to lack of detailed information, it is difficult to examine the scale of each event and to what extent victims were affected. The Public Health Indicator here refers to the frequency of water contamination events that occurred in the LYR. The scores are calculated by normalizing the statistics of Shandong and Henan.

Table 3.22 Water contamination statistics (NBSC, 2010)

Water contamination events Year	National	Shandong Province	Henan Province	Score
1995	1031	64	27	0.00
1996	677	61	7	0.29
1997	986	38	15	0.48
1998	788	-	13	-
1999	888	36	10	0.56
2000	1138	51	9	0.39
2001	1096	34	5	0.65
2002	1097	31	9	0.64

2003	1042	-	-	-
2004	753	10	6	0.94
2005	693	11	7	0.91
2006	482	8	4	0.99
2007	178	-	-	-
2008	198	5	6	1.00
2009	116	6	5	1.00
2010	135	-	8	-

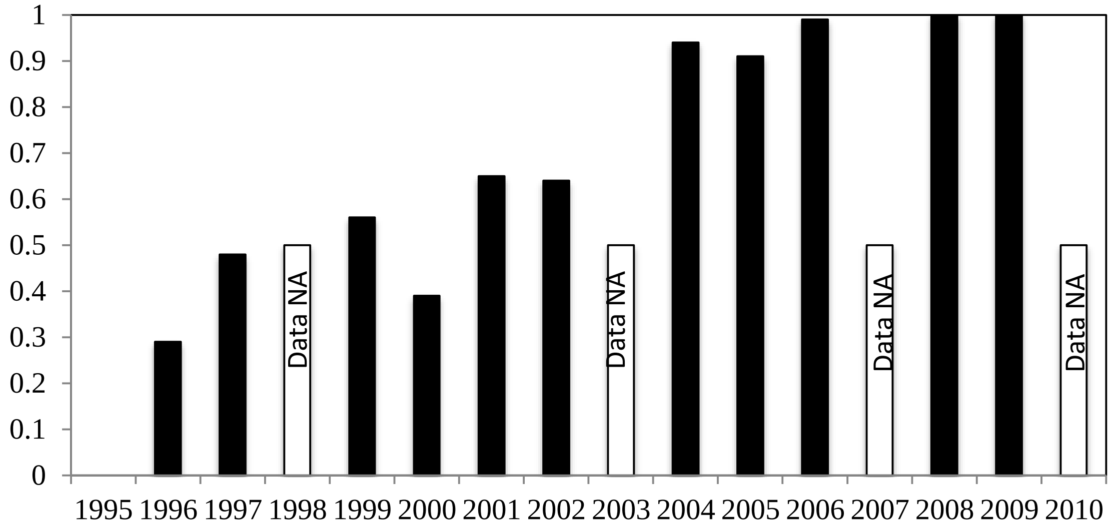


Figure 3.24 Public Health Indicator of LYR

The final results (Figure 3.24) indicate large decrease in the occurrence of water contamination events. This is likely resulted from YRCC’s efforts in water quality monitoring and water pollution control scheme.

3.5 Economic Development of LYR

3.5.1 Water Infrastructure Indicator ED_1

To regulate water and sediment, YRCC plans to construct an integrated water control system, including 36 reservoirs along the mainstream of the Yellow River. The system will also contribute to alleviating flood risk and drought risk, to allocating water resources in an efficient manner, and to better supporting regional development. Among the 36 reservoirs, there are 7 major multifunctional water infrastructures, which have a total reservoir capacity of 92 billion m^3 and account for 91.3% the reservoir capacity of the whole system. The infrastructure indicator is determined by the control areas and reservoir capacity of these 7 major multifunctional water infrastructures, as seen in Table 3.23.

Table 3.23 Major multifunctional water infrastructures along the Yellow River

Name	*Location*	*Year of Operation*	*Reservoir Capacity (10^9 m^3)*
Longyangxia	Qinghai Province, Upper Yellow River	1989	24.70
Liujiaxia	Qinghai Province, Upper Yellow River	1969	5.70
Daliushu	Ningxia Province, Upper Yellow River	TBD *	10.74
Qikou	Shanxi and Shaanxi Provinces, Middle Yellow River	TBD	12.57
Guxian	Shanxi and Shaanxi Provinces, Middle Yellow River	TBD	16.57
Sanmenxia	Shanxi and Henan Provinces, Lower Yellow River	1961	9.64
Xiaolangdi	Henan Province, Lower Yellow River	2000	12.65

*TBD refers to projects not yet started (YRIHR, 2009)

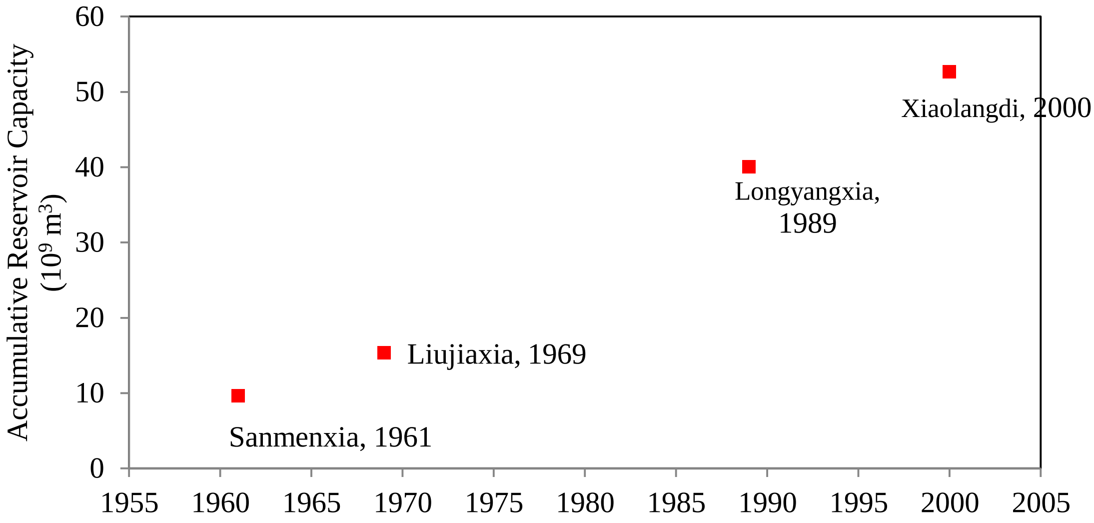


Figure 3.25 Development of major multifunctional water infrastructures

The Water Infrastructure Indicator score is calculated by,

$$ED_{1,i} = \frac{RC_i}{RC_{exp}} \tag{3.26}$$

where RC_i is the accumulative reservoir capacity of major multi-functional water infrastructures in year i; RC_{exp} is the total reservoir capacity of the 7 major multi-functional water infrastructures. The value of RC_{exp} is 92.57 10^9 m^3.

The calculation of the infrastructure indicator and the hydropower indicator (in section 3.5.2) both imply that perfect sustainabiltiy status will be achieved when all currenetly major infrastructure development is complete and fully operating. This judgement is based on the assumption that, the infrastructure and hydropower developmment plans are made to meet both current and future needs. Therefore, the results indicate whether these infrastructure have the capacity/growing capacity to continuously meet the needs. The results presented in Figure 3.27 show gradual improvement in infratructure capacity, expecially after 1988.

3.5.2 Hydropower Indicator ED_2

There are 36 reservoirs along the mainstream of Yellow River which function as the major hydropower stations. Compared to major multifunctional water infrastructures, many small to medium scale reservoirs have very limited water storage capacity but could be equipped with high installation capacity for hydropower generation.

Table 3.24 lists all the 36 reservoirs in the water control system, from the upper to the lower reaches of the Yellow River.

Table 3.24 36 major hydropower stations of the Yellow River (YRIHR, 2009)

Name	Location	Installed capacity (MW)	Annual Hydropower generation (10^9 kW h)	Year of operation
Longyangxia*	Qinghai Province, Upper Yellow River	1280	0.59	1989
Laxiwa		4200	10.22	U/C **
Nina		160	0.76	2003
Shanpin		160	0.66	TBD ***
Lijiaxia*		2000	6.06	1997
Zhiganglaka		192	0.76	2005
Kangyang		283.5	0.99	2007
Gongboxia		1500	5.14	2004
Suzhi		225	0.88	2005
Huangfeng		225	0.87	U/C
Jishixia		1020	3.36	U/C
Dahejia		220	0.84	TBD
Sigouxia		240	0.97	U/C
Liujiaxia		1690	6.05	1969
Yanguoxia	Ganxu Province, Upper Yellow River	472	2.24	1961
Bapanxia		252	1.1	1975
Hekou		74	0.39	TBD
Chaijiaxia		96	0.49	2007
Xiaoxia		230	0.96	2002
Daxia		324.5	1.59	1996
Wujinxia		140	0.68	U/C
Daliushu*	Ningxia Province, Upper Yellow River	2000	7.79	TBD
Shapotou		120.3	0.61	2007

Qingtongxia		324	1.37	1968
Haibowan	Inner Mogolia, Upper Yellow River	60	0.31	TBD
Sanshenggong		N/A	N/A	TBD
Wanjiazhai	Shanxi and Inner Mogolia, Middle Yellow River	1080	2.75	2000
Longko		420	1.3	U/C
Tianqiao	Shanxi and Shaanxi Provinces, Middle Yellow River	128	0.61	1977
Qikou*		1800	4.36	TBD
Guxian*		2100	7.10	TBD
Ganzepo		440	1.30	TBD
Sanmenxia*	Shanxi and Henan Provinces, Lower Yellow River	410	1.20	1961
Xiaolangdi*	Henan Province, Lower Yellow River	1800	5.85	2000
Xixiayuan		140	5.80	2007
Taohuayu		N/A	N/A	TBD
TOTAL		25806.3	85.94	

* Highlighted are the major multifunctional water infrastructures

** U/C refers to projects under construction

*** TBD refers to projects not yet started

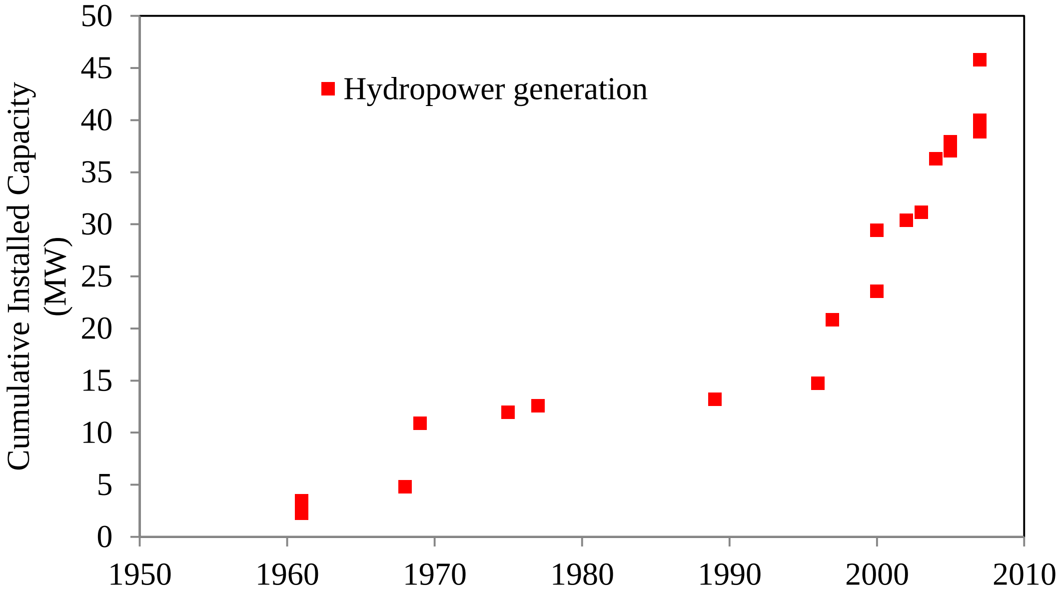


Figure 3.26 Development plans for hydropower generation

Installed capacity sub-indicator (IC) is calculated by,

$$IC = \frac{IC_i}{IC_{exp}} \tag{3.27}$$

where IC_i is the accumulative installed capacity of major hydropower stations in year i; and IC_{exp} is the total installed capacity of the 36 major hydropower stations. The value of IC_{exp} is 25806.3 MW.

Annual hydropower generation sub-indicator (AG) is calculated by,

$$AG = \frac{AG_i}{AG_{exp}} \tag{3.28}$$

where AG_i is the annual hydropower generated in year i; AG_{exp} is the expected annual hydropower generation of the 36 major hydropower stations. The value of $\mathrm{AG}_{\mathrm{exp}}$ is 85.94 109 kW h.

The Hydropower Indicator is the mean of the installed capacity (IC) and hydropower generation (AG).

$$ED_{2,i} = 0.5 \times \left(IC_i + AG_i \right) \tag{3.29}$$

The results presented in Figure 3.28 indicate significant progress in hydropower defelopment since 1996.

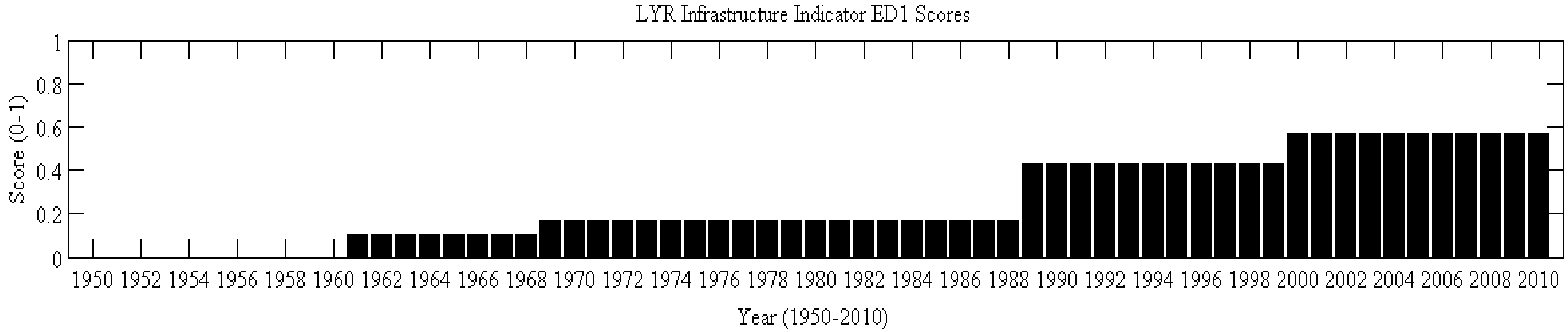


Figure 3.27 LYR Infrastructure Indicator Scores, from 1950 to 2010

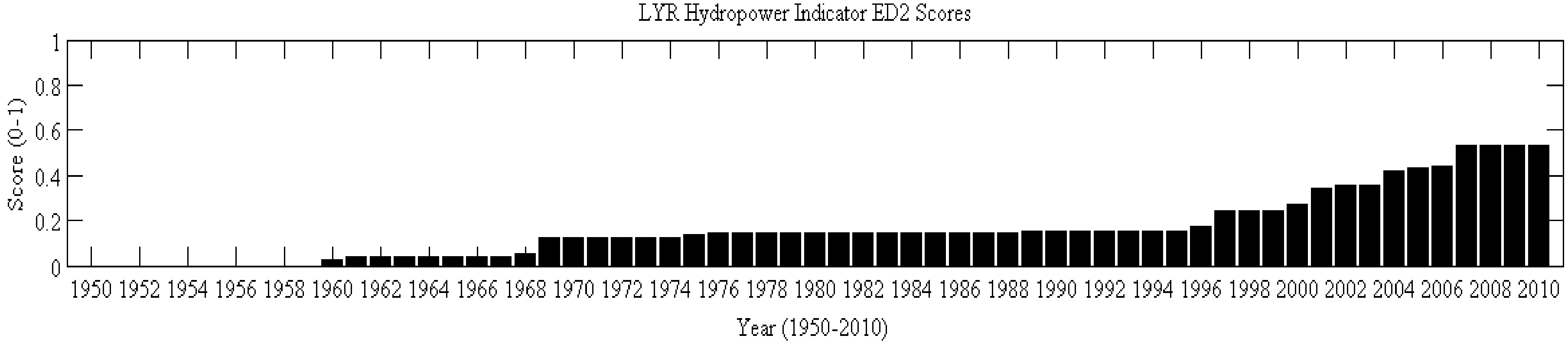


Figure 3.28 LYR Hydropower Indicator Scores, from 1950 to 2010

3.5.3 Water Supply Indicator ED_3

Water utilities are fundamental to urban development. Along with the increase in water access rate, the capacity of urban water supply developed quickly from a total capacity of 2.4 million m^3/day in 1949, to 287 million m^3/day in 2010 (as seen in Figure 3.29). Due to unavailability of regional data, the national water supply capacity data set is used as a surrogate. It is assumed that provinces in LYR experience similar trends to that for the nationwide development of water supply utilities.

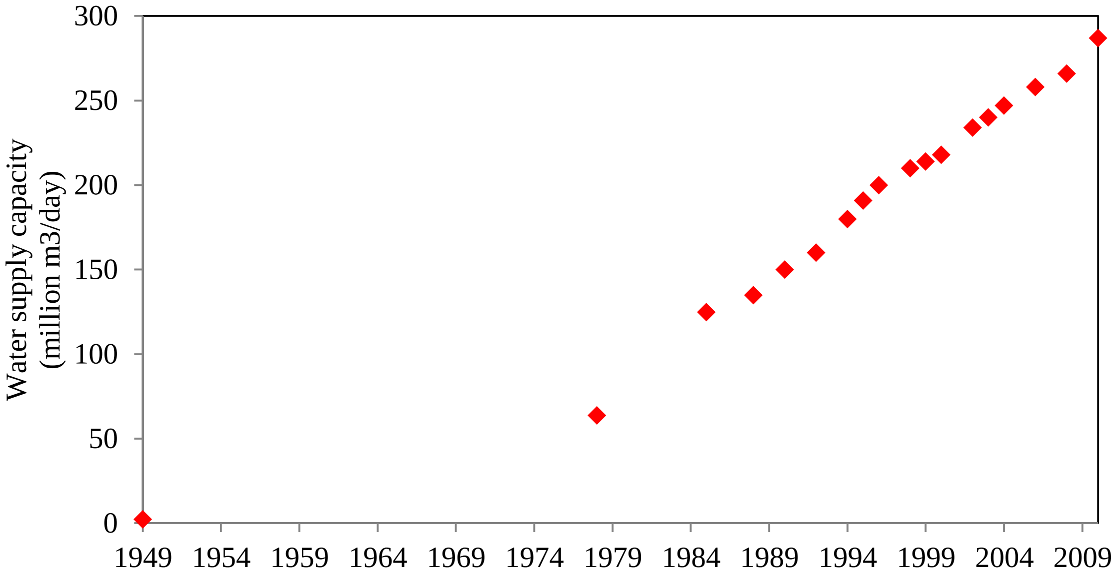


Figure 3.29 China’s water supply capacity from 1949 to 2009

The Water Supply Indicator score is calculated by rescaling as,

$$ED_{3,i} = \frac{SC_i}{SC_{max}} \tag{3.30}$$

where SC_i refers to water supply capacity in the year i; and SC_{max} refers to maxmium water supply capacity from 1949 to 2010 (287 million m^3/day).

The results are presented in Figure 3.30, showing continous growth in water supply capacity over the past 60 years.

3.5.4 Wastewater Treatment Indicator ED_4

Unlike the steady increase in water supply capacity since the 1980s, the development of wastewater treatment utilities was backward. According to MWR, there were only 315 urban waste treatment plants across China in the year 2001, with over half of 661 cities lacking facilities to treat municipal wastewater. Moreover, the sewerage network was underdeveloped in most cities, which resulted in a relatively low percentage of wastewater been collected by sewerage network. As a result, over two thirds of municipal wastewater was discharged directly into LYR without treatment in 2001 (estimated by MWR).

Wastewater Treatment Indicator is determined by the capacity of wastewater treatment utilities in Henan and Shandong provinces in LYR. Normalized score is calculated as

$$ED_{4,i} = \left({}^{D_i}\!\big/_{T_i} \right)^2 \qquad (3.31)$$

where D_i is the total wastewater discharged by Henan and Shandong Provinces in the given year i; T_i is the total wastewater treated up to national standard by Henan and Shandong Provinces in the given year i.

Raw data and aggregated scores are given in Table 3.25. Final results are presented in Figure 3.31. It indicates fast growth in wastewater treatment utilities since 1995, and has achieved a sustainable level (0.8) since 2001.

Table 3.25 Wastewater treatment statistics of Henan and Shandong in LYR

	Total Wastewater Discharged (BCM)			Total Wastewater Treated Up to Standard (BCM)			Percentage of treatment (%)		
Year	Henan	Shandong	National	Henan	Shandong	National	Henan	Shandong	National
1995	1.47	1.82	23.33	0.48	0.45	12.29	32.9%	25.0%	52.7%
1996	0.91	1.01	20.59	0.46	0.48	12.17	50.5%	47.4%	59.1%
1997	0.92	0.96	18.83	0.53	0.51	11.65	58.3%	53.4%	61.8%
1998	0.91	1.17	20.06	0.63	0.75	12.32	68.8%	63.6%	61.4%
1999	0.95	1.08	19.73	0.67	0.84	13.16	71.0%	77.9%	66.7%
2000	1.09	1.10	19.42	0.88	1.03	14.93	80.9%	93.1%	76.9%
2001	1.10	1.15	20.26	0.95	1.08	17.69	85.8%	94.0%	87.3%
2002	1.10	1.15	20.26	0.95	1.08	17.69	85.8%	94.0%	87.3%
2003	1.14	1.07	20.72	1.03	1.03	18.30	90.1%	96.4%	88.3%
2004	1.17	1.29	22.11	1.10	1.25	20.06	93.7%	97.0%	90.7%
2005	1.23	1.39	24.31	1.14	1.37	22.17	91.9%	98.2%	91.2%
2006	1.30	1.44	24.02	1.21	1.42	21.78	93.0%	98.0%	90.7%
2007	1.34	1.67	24.66	1.26	1.63	22.61	94.0%	98.1%	91.7%
2008	1.33	1.77	24.17	1.26	1.75	22.34	94.9%	98.9%	92.4%
2009	1.40	1.83	23.44	1.35	1.80	22.09	96.1%	98.6%	94.2%
2010	1.50	2.08	23.75	1.46	2.05	22.64	97.4%	98.4%	95.3%

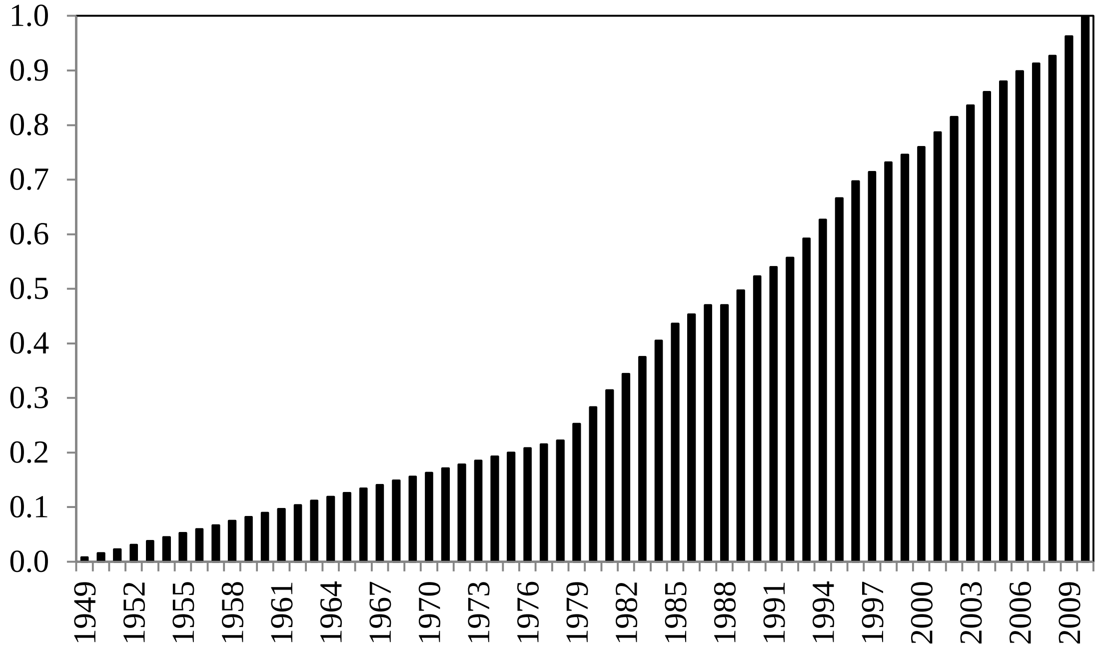


Figure 3.30 Water Supply Indicator ED_3 for LYR

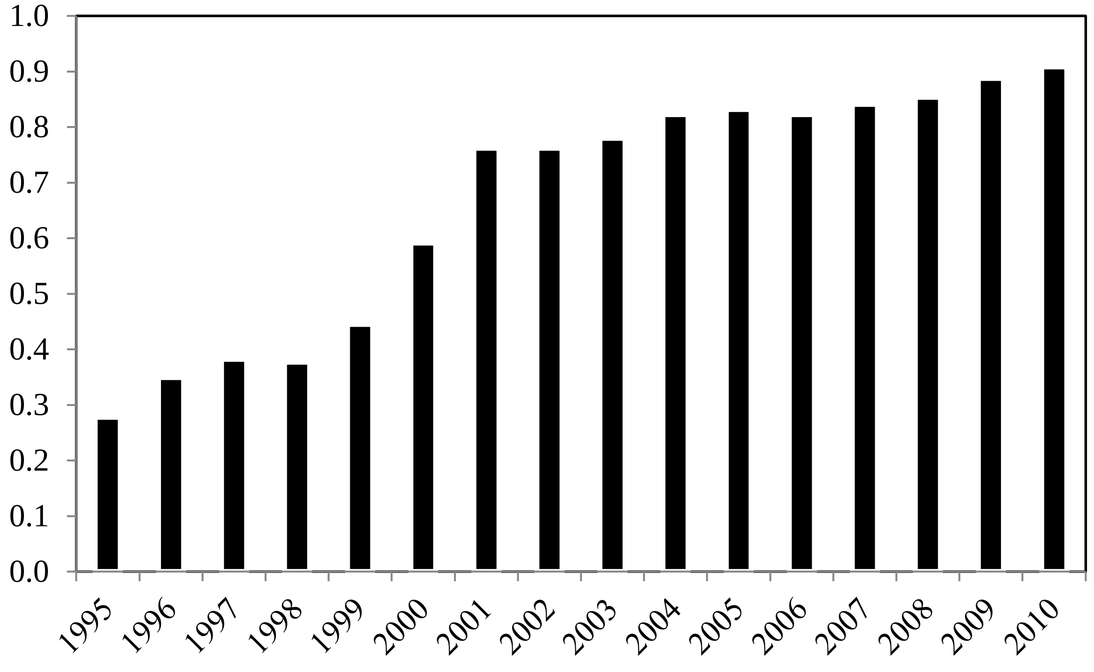


Figure 3.31 Wastewater Treatment Indicator ED_4 for LYR

3.5.5 Financial Capacity Indicator ED_5

The Financial Capacity Indicator is determined by the financial investment in infrastructures, institutions, capacity building, just to name a few, to promote institutions to management the LYR. Due to no data available, GDP is used as a surrogate indicator, based on the assumption that there is a direct correlation between GDP and the budget of YRCC and local government agencies. This is because managing LYR requires intensive manpower as well as vast investment in infrastructure development.

GDP data of Hennan Province and Shandong Province are obtained from the National Economic and Social Development Statistics Bulletin (1980-2010). The raw data (GDP in CNY) are converted to GDP in USD. And to correct the effects of inflation, the GDP in a given year is adjust to Purchasing Power in that year. To enable a temporal comparison, the GDP in 2010 is set as the benchmark of sustainable. This is based on the feedback gained from stakeholder's interview and China's 12th Five Year Plan that, the government has put much efforts and budget/capital in development infrastructures in LYR, and to improve capacity building of YRCC. The Financial indicator is calculated as follows:

- If $GDP_i < GDP_{2010}$,

$$ED_{5,i} = log_{10}GDP_i / log_{10}GDP_{2010} \qquad (3.32)$$

- If $GDP_i \geq GDP_{2010}$,

$$ED_{5,i} = 1 \qquad (3.33)$$

where GDP_i is the total GDP (billion USD) of Henan and Shandong Provinces in the year i, and GDP_{max} is the maximum GDP for the period of 1978 to 2010.

Table 3.26 GDP of Henan and Shandong Provinces in LYR

Year	GDP of Henan	GDP Shandong	Total GDP	Purchasing Power	Indicator Score
	Billion CNY	Billion CNY	Billion USD	Billion USD	
1980	22.92	29.21	34.8	28.40	0.45
1981	24.97	34.66	34.97	34.73	0.48
1982	26.33	39.54	34.81	40.81	0.50
1983	32.8	45.98	39.87	50.23	0.53
1984	37	58.16	40.89	60.00	0.55
1985	45.17	68.05	38.56	66.73	0.57
1986	50.29	74.21	36.06	71.60	0.58
1987	60.96	89.23	40.35	84.53	0.60
1988	74.91	111.77	50.15	96.95	0.62
1989	85.07	129.39	56.96	106.53	0.63
1990	93.47	151.12	51.13	119.26	0.65
1991	104.57	181.05	53.66	134.94	0.66
1992	127.98	219.65	63.04	155.39	0.68
1993	166.02	277.04	76.89	175.77	0.70
1994	221.68	384.45	70.33	203.55	0.72
1995	298.84	495.34	95.1	239.43	0.74
1996	363.47	588.38	114.49	274.78	0.76
1997	404.11	653.71	127.61	306.12	0.78
1998	430.82	702.14	136.85	334.53	0.79
1999	451.79	749.38	145.1	364.54	0.80
2000	505.3	833.75	161.75	406.91	0.81
2001	553.3	919.5	177.94	448.45	0.83
2002	603.55	1027.55	197.06	501.69	0.84
2003	686.77	1207.82	228.9	579.97	0.86
2004	855.38	1502.18	284.84	692.75	0.89
2005	1058.74	1836.69	353.46	839.84	0.91
2006	1236.28	2190.02	429.8	988.32	0.93
2007	1501.25	2577.69	536.42	1124.79	0.95
2008	1801.85	3093.33	704.84	1280.42	0.97
^{r}2009	1948.05	3389.67	781.4	1611.91	1.00
^{r}2010	2309.24	3916.99	919.75	1505.21	0.99

The results presented in Figure 3.32 show continuous increase in financial capacity since 1980, with fast-paced growth since 2000.

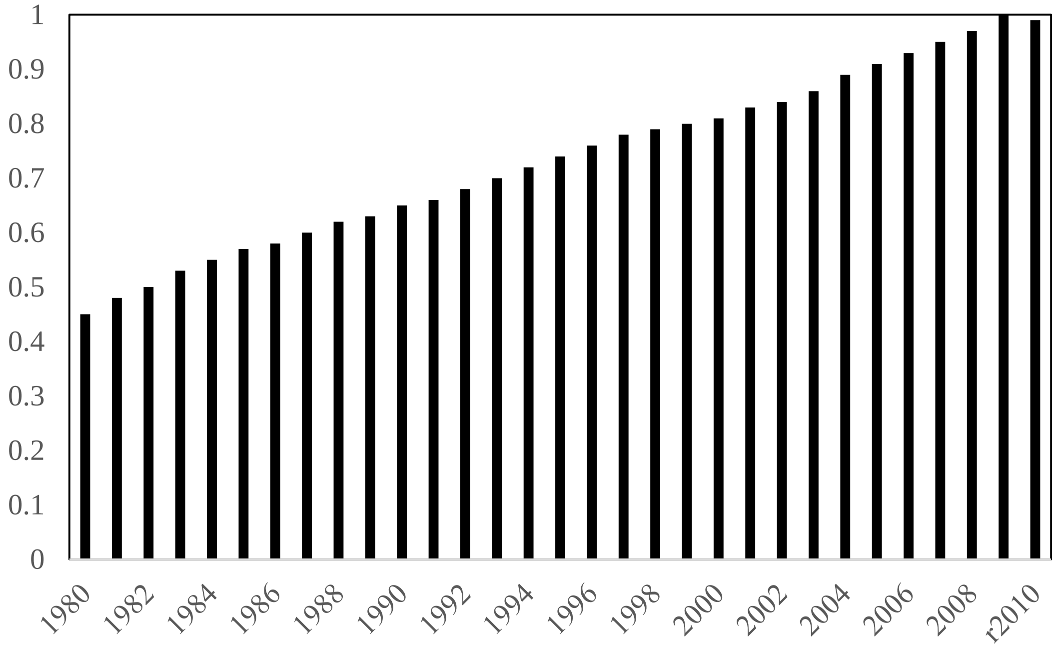


Figure 3.32 LYR Financial Capacity Indicator

3.6 Results and Discussion

3.6.1 Composite Sustainability Indices

In order to gain a holistic view of river sustainability, a composite index is constructed for each domain, namely, the Environmental Performance Index (*EPI*), Social Wellbeing Index (*SWI*) and Economic Development Index (*EDI*). The Composite indices condense and categorize the multi-dimensional information regarding the river's performance, further helping identify any trade-offs between the environmental capital, social and economic capital.

The calculation of a composite index in this research is followed by the OECD guidelines (Nardo et al., 2005) : the "ideal sequence" of ten steps to construct a composite sustainability index, from the development of a theoretical framework to virtualization of the results (see Table 3.27).

Table 3.27 10 steps for building a composite index (Nardo et al., 2005)

Steps	*Details*
1. Theoretical framework	Provides the basis for the selection and combination of variables under a fitness-for-purpose principle.
2. Data selection	Based on the analytical soundness, measurability, country coverage, and relevance of the indicators to the phenomenon being measured and relationship to each other.
3. Imputation of missing data	In order to provide a complete dataset
4. Multivariate analysis	Study the overall structure of the dataset, assess its suitability, and guide subsequent methodological choices
5. Normalisation	Renders the variables comparable
6. Weighting and aggregation	Should be done along the lines of the underlying theoretical framework.

7. Uncertainty and sensitivity analysis	Assess the robustness of the composite indicator in terms of e.g., the mechanism for including or excluding an indicator, the normalisation scheme, the computation of missing data, the choice of weights, the aggregation method.
8. Back to the data	Reveal the main drivers for an overall good or bad performance.
9. Links to other indicators	Correlate the composite indicator (or its dimensions) with existing (simple or composite) indicators as well as to identify linkages through regressions.
10. Visualisation of the results	Visualisation can influence or help to enhance interpretability

There are various methods available for calculating composite indices (as seen in Table 3.28).

Table 3.28 Methods for calculating composite indices OECD (2002a, b)

Method	Equations
1. Sum of country rankings	$CI_c^t = \sum_{i=1}^{N} Rank_{ic}^t$
2. Number of indicators above the mean minus the number below the mean	$CI_c^t = \sum_{i=1}^{N} sgn\left[\frac{x_{ic}^t}{x_{EUi}^t} - (1+p)\right]$
3. Ratio or percentage differences from the mean	$CI_c^t = \frac{\sum_{i=1}^{N} w_i y_{ic}^t}{\sum_{i=1}^{N} w_i}$, where $y_{ic}^t = \frac{x_{ic}^t}{x_{EUi}^t}$
4. Percentage of annual differences over consecutive years	$CI_c^t = \frac{\sum_{i=1}^{N} w_i y_{ic}^t}{\sum_{i=1}^{N} w_i}$, where $y_{ic}^t = \frac{x_{ic}^t - x_{EUt}^t}{x_{ic}^t}$
5. Standardized values	$CI_c^t = \frac{\sum_{i=1}^{N} w_i y_{ic}^t}{\sum_{i=1}^{N} w_i}$, where $y_{ic}^t = \frac{x_{ic}^t - x_{EUt}^t}{\sigma_{EUi}^t}$

6. Re-scaled values	$CI_c^t = \frac{\sum_{i=1}^{N} w_i y_{ic}^t}{\sum_{i=1}^{N} w_i}$, where $y_{ic}^t = \frac{x_{ic}^t - \min\left(x_t^i\right)}{range\left(x_t^i\right)}$

where IC_c^t is the value of the composite indicator for country c at time t; x_{ic}^t is the value of indicator i; w_i is the weight given to indicator i in the composite index. In Method 2, p is an arbitrarily chosen threshold above and below the mean.

In our research, integrated scores for *EPI*, *SWI* and *EDI* are calculated as follows in a similar way. The equation for *EPI* is as below,

$$EPI_i = \sum_{j=1}^{n} EP_{j,i} / n \tag{3.34}$$

where EP_i is integrated environmental performance score of the given year i; $EP_{j,i}$ refers to the normalized score of the j^{th} indicator in the environmental performance domain for the given year i; and n is the number of available indicators in the environmental performance domain in that given year.

Where there is no value for an indicator in a given year, that indicator is excluded in the composite index. For instance, There was no data/scores available for the Financial Capacity Indictor before 1980, then this indicator is excluded in the *EDI* until 1980.

The final results are presented in Figure 3.33, indicating that the overall environmental performance of LYR fluctuates over time. The worst situations are found in early 1970s and 1990s, mainly caused by excessive sediment and prolonged droughts respectively. This is also the period of time when China's economy taken off after the *Open Door Policy*. Increasing demand for water resources and excessive discharge of wastes caused much damage to the health of Yellow River. *EPI* has gradually improved since 2002, owing to the implementation of IRBM policy, namely, maintaining healthy life of the Yellow River, by MWR in 2002. Associated with that, the establishment of Xiaolangdi Multifunctional Infrastructures has significantly improved the water-sediment nexus in the LYR. With the capacity to store flood water and regulate environment flow in the dry steam, Xiaolangdi also captures the sediment and flushes it twice a year to improve river channel capacity in the LYR. It has effectively evened the discharge over a hydrological year, maintained a continuous flow in the LYR and improved the channel capacity through flushing the silt.

The general social wellbeing in the LYR has been maintained at a stable, acceptable level; yet, a trade-off between water consumption (Figure 3.19) and water access (see Figure 3.20) can be identified. This reveals the inherent drawback of using an integrated index, which may average out of the extremes, hide important details and may result in loss of key information.

The *SWI* is predicted to improve in the next decade in the view of the ongoing China's South-North Water Transfer Project, which aims to transfer 44.8 BCM water resource from the Yangtze River Basin to the Northern provinces of China (Xinhua, 2011). This will provide LYR with a new major water source, reduce drought risks and water allocation stress.

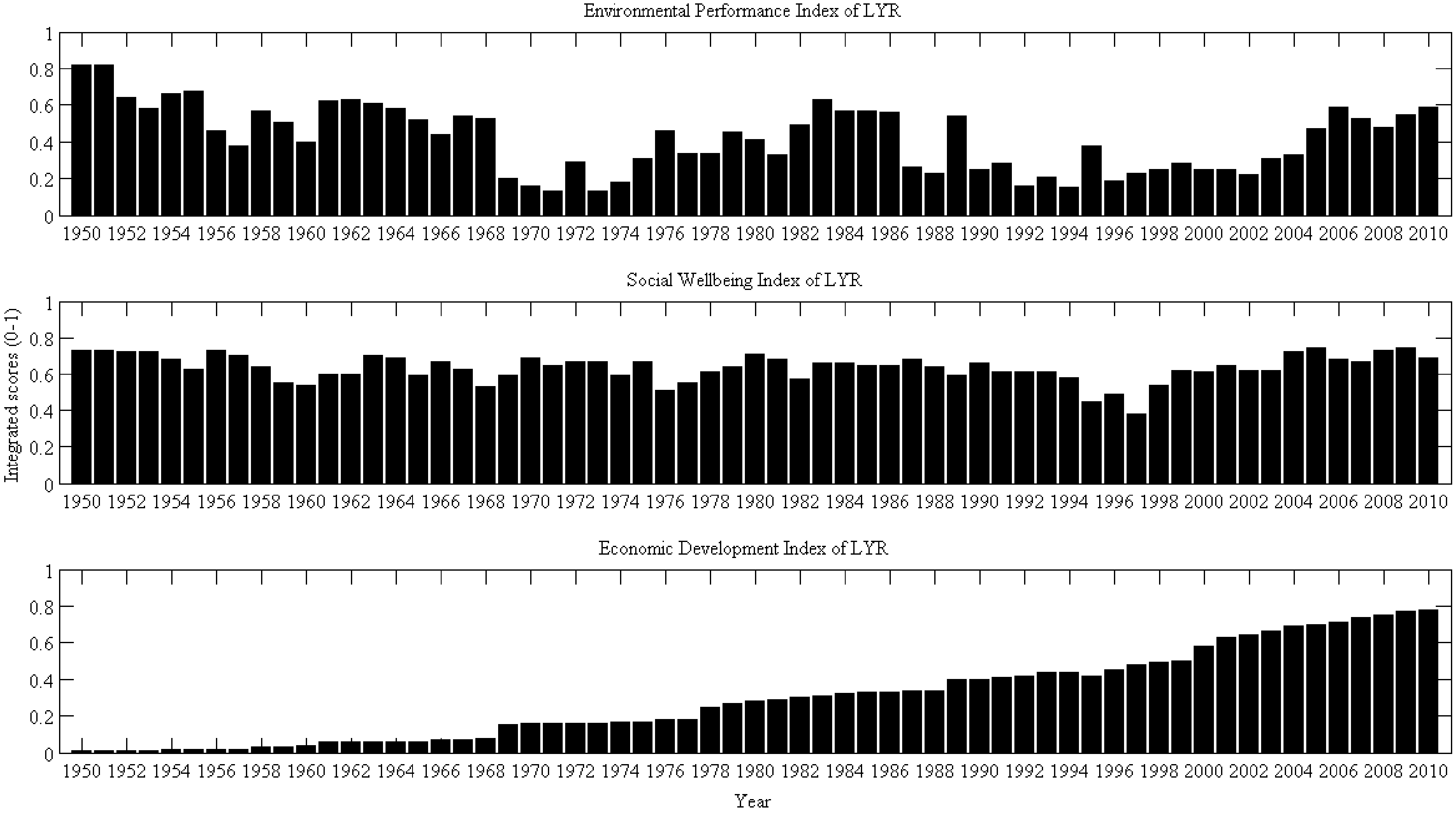


Figure 3.33 Environmental Performance Index, Social Wellbeing Index and Economic Development Index of LYR

For the economic development domain, a continuous, robust growth has been identified over the study period. This is because of extensive development of infrastructures for hydropower generation, flood defense, and water utilities associated with fast GDP growth.

It is noted that the development infrastructure has brought many debates. The complex impacts of large-scale infrastructure on the environment are not examined in *EDI*. This is due to the fact that the *EDI* focuses on capacity of infrastructure, whilst environmental impacts are counted by indicators in the environmental performance domain. The trade-offs between the three domains will be discussed in detail in next chapter (section 5.2).

3.6.2 Composite Index to Measure Specific Concern

By using the PAM methodology, the assessment framework consist of a set of indicators which are specific to measure one problem respectively, non-overlapping, and aggregated to the same scale. Thus enables us to compile a selection of indicators an index for measuring a specific concern. Here are two examples:

Water and Sediment Index

The Water and Sediment Index (WSI) aims to measure the status of water and sediment in the Lower Yellow River, which presents the greatest concern of river managers at both local and basin level. Instead of modelling the dynamics between water and sediment or examining the correlation between the two, this index gives an overview of the general hydrological condition of water and sediment in the LYR, by a grade from 0 to 1 referring to bad to good status. This provides simplified information for policy-makers and river managers to understand the change over time and the overall trend.

WSI is built on the Environmental Flow Indicator and Sediment Transport Indicator, with equal weightings given to each indicator. *WSI* is calculated as follow,

$$WSI_i = 0.5 \times \left(EP_{1,i} + EP_{4,i} \right) \tag{3.35}$$

where WSI_i is the composite score for water and sediment of the given year i; $EP_{1,i}$ and $EP_{4,i}$ are scores of the Environmental flow indicator and sediment transport indicator of the given year i.

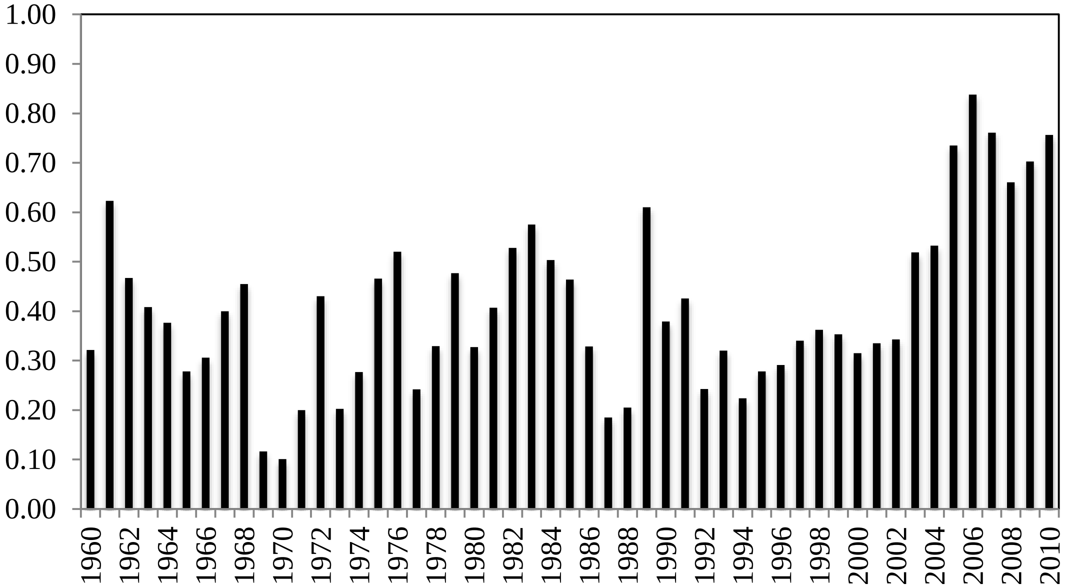


Figure 3.34 Water and Sediment Regulation Index of LYR

The results of *WSI* are presented in Figure 3.34, showing large variations from 1960 to 2000 with the worst situations occurring in 1969 and late 1990s. The general condition has improved since 2003, with an upward trend evident and exhibits less fluctuation over time. This result corresponds to the establishment of Xiaolangdi in 2003 correctly, which demonstrates the capacity of *WSI* in identifying the change.

Water Utilities Index

The Water Utilities Index (WUI) measures development of urban water supply and wastewater treatment facilities. This index reflects MDGs' concerns about access to water supply and sanitation for social development, and the extent to which the water utilities can meet these needs.

WUI is based on Water Access Indicator, Wastewater Discharge Indicator, Water Supply Indicator and Wastewater Treatment Indicator. It is calculated as follow,

$$WUI_i = 0.25 \times \left(SW_{4,i} + SW_{5,i} + ED_{3,i} + ED_{4,i} \right) \qquad (3.36)$$

where WSI_i is the composite score for water and sediment of the given year i, *and* SW_4, SW_5, ED_3, ED_4 refers to the Water Access Indicator, Wastewater Discharge Indicator, Water Supply Indicator and Wastewater Treatment Indicator respectively.

The final result of *WUI* is presented Figure 3.35. It shows rapid development in water utilities since the mid-1990s. It is likely to continue growing in the next few years, evidenced from new infrastructure comes into operation according to China's 12th Five-Year-Plan (KPMG, 2011).

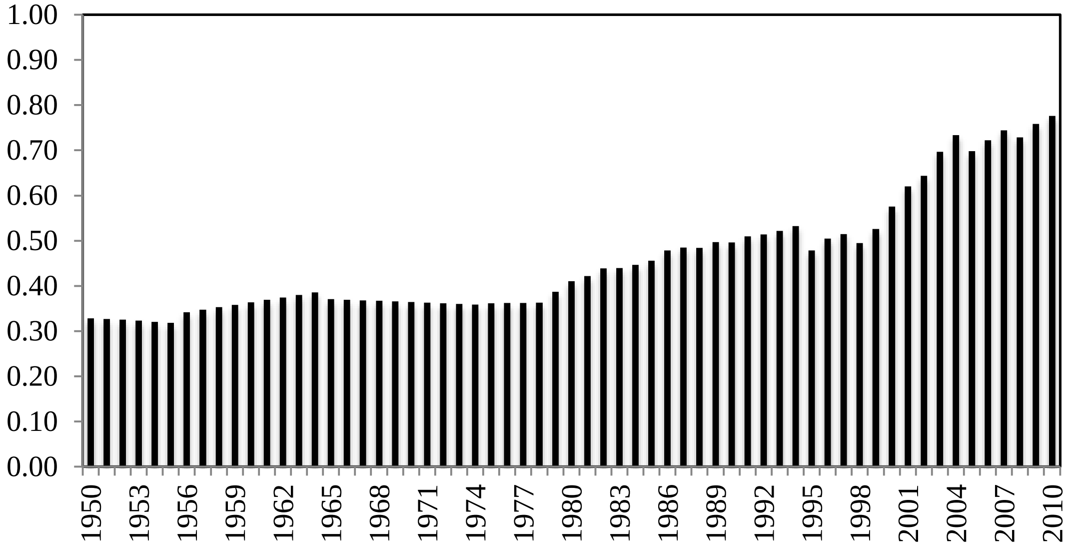


Figure 3.35 Water Utilities Index of LYR

CHAPTER 4. Upper Ganges River Sustainability Assessment

4.1 Background

The Ganges is one of the most densely populated and fertile river basins in the world. The Ganges basin extends through India, Nepal and Bangladesh. In India, the length of the Ganges is 2,525 km, where the catchment area is approximately 0.86 million km^2. The surface water resource of the Ganges is estimated at 525 billion m^3 per year (O'Keeffe et al., 2009), the main sources of which are rainfall and snow melt from glaciers. The Ganges river basin constitutes 26% of the land area of India, and supports about 43% of its population (Kamyotra, 2009). There are approximately 500 million people dependent on the river and its tributaries. According to the India National Census of 2001, the population of major cities and towns within the Ganges river basin increased by 32% from 1991 to 2001. Consequently, the ecological state of the Ganges is significantly affected by human activities.

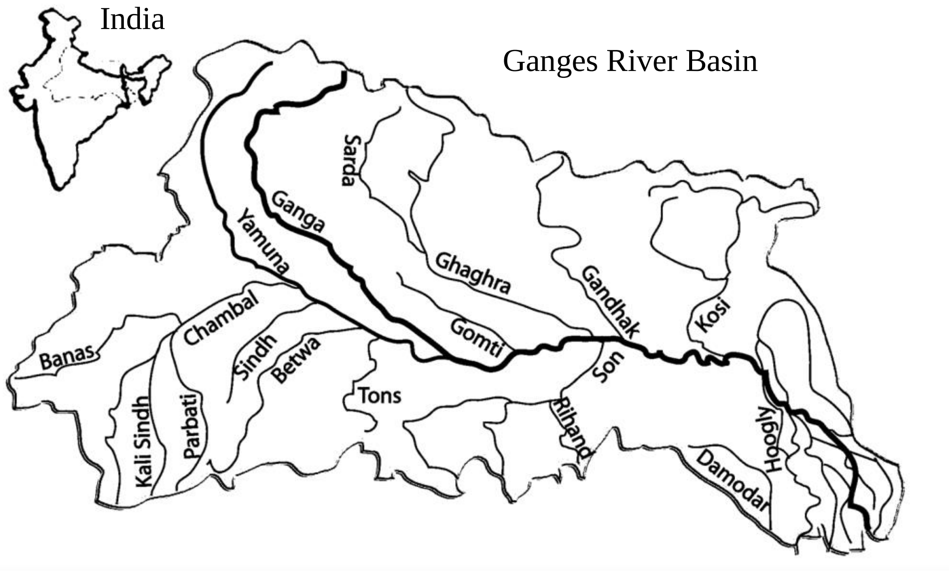


Figure 4.1 Map of Ganges River basin in India (Gangapedia, 2014)

The main sources of water in river Ganges come from rainfall, subsurface flows and snow melt from glaciers. The annual average rainfall in the basin varies significantly, falling between 39 cm to 200 cm, with an average of 110 cm. 80% of the rainfall occurs during the monsoon months (June and October). Due to large temporal variations in precipitation, there is wide fluctuation in the flow characteristics of the river. The Himalayan Mountains, surrounded by snowfields and glaciers, is another important water source. In the upper Ganges basin, all the tributaries are assured water supply throughout the year.

The river flows through a total of five states, carved out of the Himalayas and adjoining districts of Uttar Pradesh. Uttarakhand borders Tibet to the north, Nepal to the east, and the states of Himachal Pradesh and Uttar Pradesh in the west and south respectively (Savoskul and Smakhtin, 2013). In order to characterize the river in its different reaches, homogenous zones are defined according to the changing gradient and consequent geomorphological conditions overlain by land uses and river channel (O'Keeffe et al., 2009, TERI, 2011).

The Ganges has one of most densely populated river basins in the world. According to 2001 census of India, the average population in the Ganga basin is 520 persons per km^2 as against 312 for the entire country. Major cities i.e. Dehradun, Delhi, are situated in the basin. These cities have large and growing populations, along with fast expanding industrial bases. Between 1991 and 2001, the urban population increased by 32% from

88.2 million to 116.6 million. This trend of population growth is likely to continue. The pollution load is expected to increase correspondingly, with ever-growing stress on the water quality.

One unique characteristic of the Ganges is its sociocultural significance, especially for the pilgrimage of Hindus. In Hindu mythology, the Ganges is embodied with sacred water. Hindus bathe in its waters, paying homage to their ancestors and gods by the riverside, carry small quantities of water back home for use in rituals, and when a Hindu dies, the family would bring the ashes of the deceased person to the Ganges. In the Upper Ganges, Rishikesh and Haridwar predominantly support livelihoods related to culture, religion and entertainment. Both places are sacred pilgrimage sites for people from the plains, with millions of pilgrims visiting for ritual bathing on auspicious days. *Ganga Aarti* takes place in Rishikesh and Haridwar twice a day, at sunrise and sunset time. *Aarti* refers to a Hindu ritual of worship in which lights with wicks soaked in ghee are lit and offered up to one or more deities. *Aarti* held at sunset at Haridwar usually attracts thousands of participants. Another major event, the *Kumbh Mela*, is a mass Hindu pilgrimage of faith in which Hindus gather to bathe in a sacred river, which is held every 13 years (PSI, 2013a). The Maha *Kumbh Mela* held in 2013, involved more than (an estimated) 100 million visitors, and was considered to be largest peaceful gathering in the world (Spinney, 2013). Accordingly, a large part of the local population depends on these pilgrims for their livelihood (Mohan and Sinha, 2011).

4.2 Applying PAM to the Ganges

4.2.1 Field Trip

A research trip to India was undertaken from July to September of 2013. The purpose of the trip was to carry out a case study of the Ganges, using PAM to examine the underlying sustainability of the Ganges river basin. Details itineraries and research trip planning can be found in Appendix I. The researcher was based at the Council on Energy, Environment and Water, visits were paid to WWF India, Ghandi Peace Foundation and People Science Institute. A trip was also taken to visit the upper researcher of the Ganges, a section of river course between Haridwar and Rishikesh.

Stakeholder interviews

PAM was used to develop the assessment framework. Following a comprehensive review of the Ganges, stakeholder interviews were taken during the trip to address sustainability concerns of the Upper Ganges. Table 4.1 lists the interviews conducted, with interviewees' name, position, interview date, and the topics discussed. A broad range of stakeholder were selected, including water and river basin management specialists, policy-makers and NGO leaders. Local community is another important form of stakeholder. Although none of the villagers were interviewed, a comprehensive social-cultural study report from the People Science Institute (PSI) revealed public perception on holy Ganga, river health and sustainability.

All the interviews were carried out in English in the form of semi-structure interview. A broad range of questions were asked, which were categorised under 6 themes: overall, sufficiency, resilience, access, productivity and equity. Table 4.2 provides a list of sample questions used for the stakeholder interviews. A sample of the interview note is shown in Appendix II.3. Although the interviews were not recorded or transcribed, intensive notes were taken and key information were summarized (see Table 4.3). These key information provides the basis for indicator selection.

Table 4.1 Stakeholder interviews during the field trip to Upper Ganges

Title/Name	*Position*	*Date*	*Type of Interview*	*Topics covered*
Dr Arunabha Ghosh	Director, CEEW	23/07/2013	Face-to-face;	National energy and water policies in India, integrated river basin planning, food water energy nexus, water and sanitation
Dr Nirmalya Choudhury	Senior researcher, CEEW	23/07/2013	Face-to-face;	Water resources engineering and management, integrated river basin management, flood risk analysis
Rudresh Sugam	Researcher, CEEW	25/07/2013	Face-to-face;	Water quality monitoring, water utilities and sanitation, water food energy nexus
Anumpam Mishra	Director, Ghandi Peace Foundation	28/07/2013	Face-to-face;	Environmental movement, emerging issues of the Ganges, forest conservation and anti-hydro campaigns
Dr Upali Amarasinghe	Senior researcher, IWMI India	06/08/2013	Telephone	Integrated river basin management, hydropower development, environmental flow assessment
Dr Luna Bharati	Senior researcher, IWMI Nepal	08/08/2013	Telephone	Integrated river basin management, water utilities study, biodiversity survey
Dr Anita Sharma	Researcher, PSI	27/08/2013	Face-to-face	River health assessment, socio-cultural analysis
Dr Ravi Chopra	Director, PSI	27/08/2013	Face-to-face	Sustainability concerns for the Ganges, hydropower and environment conservation, socio-economic analysis
Meena Yadav	Researcher, PSI	27/08/2013	Face-to-face	Social vulnerability assessment, social-economic development, tourism
Suresh Babu	Director, WWF India	30/08/2013	Face-to-face	National water policies, environmental flow assessment, WWF Living Ganga project, biodiversity and water quality
Yamini Panchaksharam	Senior Research, WWF India	31/07/2013	Email	Research coordination, biodiversity, land use, water quality monitoring

Table 4.2 List of Sample Questions for the Stakeholders' Interviews

Overall

1. What are the characteristics of the Ganges?
2. What distinguishes the Ganges from other rivers?
3. Please explain the socio-cultural value of the Ganges.
4. Please summarize the most pressing issues concerning the Upper Ganges?
5. What are the challenges to management the Upper Ganges?
6. Can you explain the integrated river basin management strategies for the Ganges if any?
7. What are the short-term and long-term goals with regards to managing the Upper Ganges?
8. What does a sustainable river course means to the Ganges?

Sufficiency

9. Has there been sufficient environmental flow in the Upper Ganges, and why?
10. Has the water quality in the Upper Ganges improved or degraded, and what are the possible reasons?
11. Please explain WWF's Living Ganga Project.
12. Please explain the major point source and non-point sources of wastewater discharged to the Upper Ganges.
13. Is there any evidence of biodiversity and/or habitats loss in the Upper Ganges basin?
14. What's the status of and change to forests and floodplain in the Upper Ganges?
15. Please explain the land use policies to the Upper Ganges basin.

Resilience

16. Please explain the flooding issues and risks of the Upper Ganges.
17. What are the lessons learned from the recent extreme flood event?
18. Please explain water pollution issues of the Upper Ganges.
19. What are the sources of wastewater, point and non-point?

20. Are there regulations on wastewater discharge?
21. Please explain public health issues associated with water contamination, and water-borne diseases.

Access

22. Please explain the development of water supply utilities in the Upper Ganges basin.
23. Please explain the development of sanitation facilities.
24. Please explain the development of public sewage system.
25. Please explain the development of wastewater treatment utilities.
26. Have the MDGs goals with regards to sustainable access to safe drinking water and basic sanitation been achieved, and why?

Productivity

27. Please explain the development of hydropower projects of the Upper Ganges.
28. What are the impacts of small-scale hydropower plants?
29. Please explain the agricultural activities in the Upper Ganges basin.
30. Please explain the water intensive industries activities in the Upper Ganges basin.
31. Please explain the average domestic water consumption in the Upper Ganges.

Equity

32. What are the competing needs of water in the Ganges basin?
33. Is there water allocation policies regulation in the Ganges basin?

Table 4.3 Survey of stakeholders’ opinions obtained during the field trip to UGR

Stakeholder	Key information
Dr. Ravi Chopra	*Characteristics of the Ganges* Ganges is declared as the National River of India. It symbolizes the national heritage and identity of India. In Hinduism, the river Ganges is sacred and represents the goddess Ganga. It is worshipped by Hindus who believes that bathing in the river can remission their sins

	and purify their spirits. Ganges is also one of the most densely populated and fertile river basins in the world. It provides millions of people water to support their everyday life.
	Current status of the Ganges Water in the Ganges is getting heavily polluted due to unregulated discharge of untreated sewage and industrial effluents to the river. "*Discharge of effluents from Kanpur tanneries is a big problem. It makes the water of Ganga red. There are 57 sewage lines entering Ganga in Allahabad itself"(PSI, 2013b).* Significant change in flow variations has also been identified. On the one hand, extreme events became more frequent in recent years; on the other hand, water level could get low enough for wading across during the dry season at several locations. This is most likely due to the boost in both small-scale hydropower projects and large-scale infrastructures such as the Tehri dam.
	Issues with Hydropower Development Vast hydropower development has taken place in Uttarakhand since the late 20 Century. However, there appears to have been a thoughtless rush to build these hydroelectric power projects without taking the ecological, social or economic costs into consideration.This has led to local environmental flow deficits in the lower river reaches of the hydropower off-takes, as a major use of the flow in the upper reaches is for run-of-river hydropower development. Notable changes in flow variations were observed, and hydropower projects is one major factor. Such changes are associated with potentially disastrous consequences in terms of seasonal water shortage and intensified flooding damage (Chopra, pers. comm., 2013).
Prof. Upali Amarasinghe	*Issues with hydropower development* Hydropower projects are mostly built by private sectors or joint venture with local government. Most of the projects are on a small

	scale. There lacks comprehensive environmental impact assessment on these projects. Without integrated planning, administration or regulation, hydropower development in Uttarakhand has been widely criticized for destroying the river channel, misusing the floodplain, and further intensifying flood risk in this region (Amarasinghe, pers. comm., 2013).
Dr. Arunabaha Ghosh	*Sustainability Perspectives* There are three important aspects concerning sustainability of the Ganges. Primarily, the river should maintain a good ecological state and provide sufficient water resources. Water-related risks in terms of flooding, drought and water contamination should be well managed. Secondly, access to water supply and sanitation is a fundamental entitlement. Secondly, the MDGs regarding Water, Sanitation and Hygiene (WASH) should be achieved to meet the basic needs. In addition, the sociocultural nature and ethical aspects of the river should be identified, and taken into account in river basin management. Finally, water should be efficiently used to produce food to alleviate poverty and to generate energy to support industrial development (Ghosh, pers. comm., 2013).
Anumpam Mishra	*Emerging issues* The upper reach of River Ganges suffers from many problems. These include extreme pollution levels due to agricultural and industrial effluents, and inflow of the most polluted tributaries; diversions for hydropower and excessive water abstraction from dams and barrages. Forest degradation has become more serious in the past decade. This is mainly due to expanding urban areas and development of hydropower projects. The loss of forest cover reduces the landscape's capacity to retain precipitation, further intensifying flash floods. It also increases rates of soil erosion, as well as sediment load in the river system Increasing number of tourists has caused notable impacts. On the positive side, it made great contributions to the local

	economy. However, it demands excessive resources and puts ever-growing stress on the local environment (Mishra, pers. comm., 2013).
Rudresh Sugam	*Water quality degradation* Water quality degradation has long been a significant issue concerning the Ganges. The upper reach is not an exception. This is mainly due to lack of wastewater treatment capacity resulting in a large percentage of untreated sewage being discharged into the river. As the Ganges flows through densely-populated areas, untreated domestic wastewater, agricultural and industrial effluents, together with religious offerings wrapped in non-degradable plastics discharge large amounts of pollutants to the river (Sugam, pers. comm., 2013).
Dr. Luna Bharati	*Water access* Access to water and sanitation services remains a big challenge in rural areas in Upper Ganges basin. Many poorer people who lack access to water supply, rely on the river on a daily basis for bathing, washing, and cooking (Bharati, 2008). WHO claims that 8% of all illnesses in India and one-third of deaths can be attributed to water-borne diseases, whist the World Bank estimates that the health costs of water pollution in India equal 3% of the nation’s GDP (Bharati, pers. comm., 2013).
Suresh Babu	*Ganga Action Plan* The pollution in Ganga threatens more than 140 fish species, 90 amphibian species and the endangered Ganges river dolphin (Mohan and Sinha, 2011). To prevent pollution and to improve water quality, the Ganges Action Plan was formulated in 1984 on the basis of a comprehensive survey of the Ganges Basin carried out by the Central Pollution Control Board. The objective was to restore the river water quality to the Designated Best Use class of Ganges, which is “Bathing Class”. However, the Ganga Action Plan, with an environmental initiative to clean up the river, is criticized as a major failure, due to corruption, lack of technical expertise, poor planning,

	and lack of support from religious authorities (Haberman, 2006, Singh, 2007). In face of the challenge, WWF launched the Living Ganges programme for assessing environmental flow in the Upper Ganges river basin in 2011. The programme aimed to monitor ecological conditions of the river, as the Ganges flowed from the high altitude mountain sources to the highly populated and developed mid-reaches in the plains (Babu, pers. comm., 2013).
Meena Yadav	*Booming tourism* There has been a boost in tourism in the past decade in the Uttarakhand. Tourism activities have diversified from being primarily religious, to recently including adventure activities such as camping, rafting, kayaking, tracking. Rishikesh, world-known for its yoga and meditation ashrams, also hosts the international Yoga festival every year. According to UNEP, tourism is a very complex industry involving many stakeholders (sometimes with opposite interests), and requiring significant amount of resources. On one hand, tourism has made remarkable contributions to the local economy, in terms of revenue and employment opportunities. On the other hand, it demands large quantities of natural resources, and has significant impacts on the local environment as well as social-cultural aspects. Therefore, tourism should be carefully managed in order to play a positive role in the socio, cultural, economic, environmental and political development (Yadav, pers. comm., 2013)

Set up the System Boundary

The upper reach of the Ganges was set as the geographical extent of our assessment. There are a few reasons, first, this regions faces most of the major challenges identified during literature review and the stakeholder interview, including, water quality degradation, increasing flooding risks, deforestation and vast hydropower development. Second, the 2013 Northern India flood raises much attention to this region (Lucknow, 2013), and most of our stakeholders have good insights into the status of the Upper Ganges.

Our study area, the Upper Ganges river basin, is located in Uttarakhand State in Northern India as shown in Figure 4.2. The upper reach of the Ganges for the present study ranges from Gangotri to Rishikesh. Situated in high mountains, this river section is glaciated, with a steep gradient of 15 m per 1 km and typical channel widths range from 50 m to 250 m (TERI, 2011). After flowing 250 km from its source at Gangortri, the Ganges reaches Rishikesh, before descending into the vast Indo-Gangetic plain. At this point, the river discharges into its mid-reaches, with a stream that is 750 m wide.

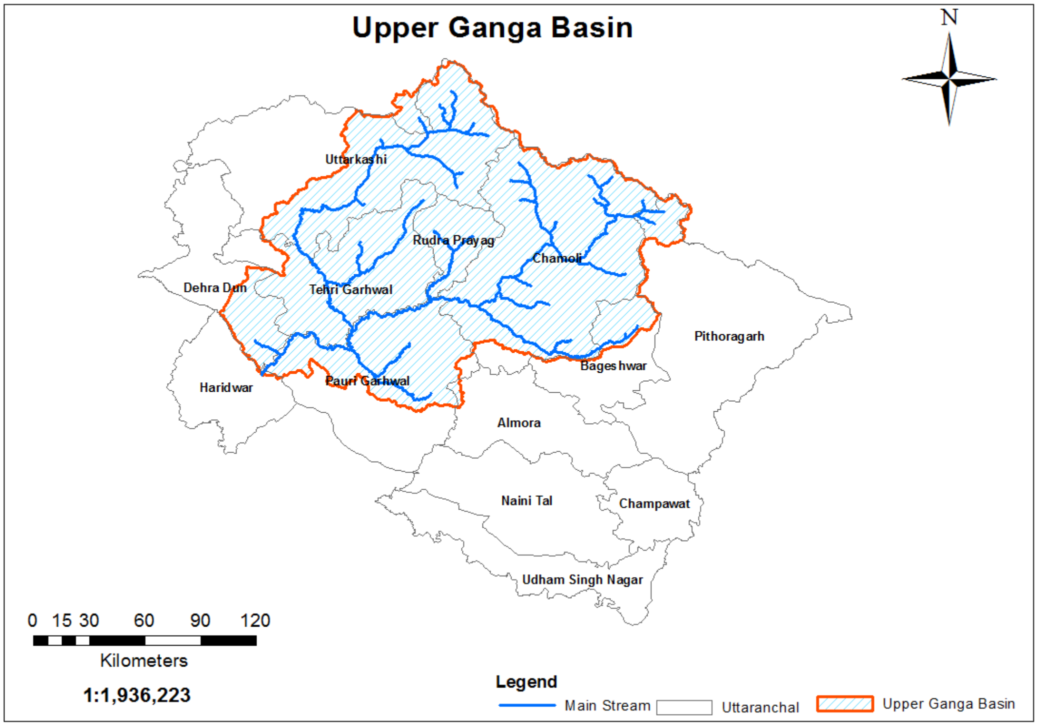


Figure 4.2 Map of Uttarakhand showing the UGR and its tributaries

The temporal boundary covers the period from 2001 to 2010. This is because Uttarkhand state was founded in 2000. Although this is insufficient to cover the intergenerational effects, it is still useful to show how the changing environment, growing societies and booming economy impact on the overall river sustainability.

4.2.2 Site Visit

A visit was paid to the Upper Ganges River basin during the field trip. The purpose was to observe religious pilgrimages, to gain better understanding of people's living experience, to interact with local researchers, and to access documentation. Figure 4.3 presents photographs taken during the field trip, featuring the upper stretch of the Ganges at Rishikesh (a), where the river reaches the Ganga plain, and Haridwar (b), where the stream becomes wider and of flatter gradient. The photographs in Figure 4.3 c. and d. are taken during the Ganga Aarti at Rishkesh and Haridwar respectively. With over ten thousand people participating on daily basis, this is one of the most important Aarti in Hindu.

a. Upper Ganges mainstream at Rishikesh, showing mountainous landscape in Upper Ganges river basin

b. Upper Ganges at Haridwar, showing the river reaching the Ganga plain, where the stream becomes wider and of flatter gradient

c. Ganga Aarti at Parmarth Niketan Ashram in Rishikesh. Aarti refers to a Hindu ritual of worship in which lights with wicks soaked in ghee are lit and offered up to one or more deities.

d. Ganga Aarti at Haridwar. With over ten thousand people participating on daily basis, this is one of the most important Aarti in Hindu.

Figure 4.3 Photographs of UGR taken during the field trip in September 2014

4.2.3 PAM for Indicator Selection

This section discusses the sustainability assessment framework development process for the Upper Ganges River Basin. Through the literature review, stakeholder interviews and site visit, a list of impact generators (IGs) are summarized, as shown in Table 4.4.

Table 4.4 List of impact generators on Upper Ganges' sustainability performance

External Impact Generators	Varying rainfall patterns Varying climate and micro-climate Extreme rainfall
Internal Impact Generators	Varying water quality Forest degradation Aquatic and wetland species management Agricultural activities Domestic and Industrial water consumption Tourist sites development Water utilities development Hydropower Development Agricultural activities Fishing activities

PAM is adopted to guide the indicator selection. Taking the selection process of Environmental Flow Indicator (EFI) for example, the process of indicator generation is as follows: *Impact Generators* (*IIGs and EIGs*) are identified as varying rainfall patterns and varying climate and microclimate. These result in specific *Issues*, including: 1) increasing uncertainty and scale in seasonal flow variation; 2) increasing uncertainties in flows from glaciers; and 3) increasing uncertainty and scale in seasonal flow variation. In respect of the perspectives of river sustainability, *Concerns* are addressed regarding *Resilience* to flow variations. And both current and future generations will be affected as *External Impact Receivers (EIRs).* Thus the flow variations are used as the measurement for *EFI*. Table 4.3 to Table 4.6 present the framework development process for the environmental, social and economic domains.

Table 4.5 PAM for indicator selection for UGR's environmental performance

Impact Generators (IIGs/EIGs)	*Impact on*	*Issue*	*Concern*	*External Impact Receivers (EIRs)*	*Indicator*
Varying rainfall patterns	Environmental flow	Increasing uncertainty and scale in seasonal flow variation.	*Resilience* to flow variation	Current and future generations	Environmental flow
Varying climate and micro-climate		Increasing uncertainties in flows from glaciers			
		Increasing uncertainty and scale in seasonal flow variation.			
Varying water quality	Water quality	Water quality degradation and increasing risk of water-borne diseases	*Sufficient supply of usable water resources*	Current and future generations	Water quality
Agricultural activities	Wastewater disposal, water quality	Non-point source water pollution	*Sufficient supply of usable water resources*	Current and future generations	Water quality
Domestic and Industrial water consumption	Wastewater disposal, water quality	Point source water pollution	*Sufficient supply of usable water resources*	Current and future generations	Water quality
Forest degradation	Land use	Loss of forest cover, loss of capability to moderate micro-climate	*Resilience* to varying habitats and ecological cycle.	Current and future generations	Forest cover

Hydropower Development	Land use	Loss of forest cover and floodplain due to land used for hydropower development	*Resilience* to varying habitats and ecological cycle.	Current and future generations	Forest cover
Aquatic and wetland species management	Biodiversity	Loss of biodiversity	*Resilience* to varying aquatic and wetland species, and biodiversity loss; Intergenerational *equity*	Future generations	Biodiversity
Hydropower Development	Environmental flow	Changing flow patterns and aquatic ecosystem	*Resilience* to varying aquatic and wetland species, and biodiversity loss; Intergenerational *equity*	Current and future generations	Biodiversity
Tourist sites development	Ecosystem	Damaging local ecosystem	*Resilience* to varying habitats and ecological cycle.	Current and future generations	Biodiversity

Table 4.6 PAM for indicator selection for UGR's social wellbeing

Impact Generators (IIGs/EIGs)	*Impact on*	*Issue*	*Concern*	*External Impact Receivers (EIRs)*	*Indicator*
Water utilities development	Water provision	Improving life quality in terms of hygiene and public health	Access to public water supply, as human right to water	Current generations	Water supply
	Sanitation and sewage	Improving life quality in terms of hygiene, public health and dignity,	*Access* to modern sanitation and public sewage system.	Current and future generations	Sanitation
		Reducing risk of water contamination and water quality degradation, Lowering risk of water-borne disease	Access to public water supply, modern sanitation and public sewage system.	Current and future generations	Water supply and sanitation
Domestic and Industrial water consumption	Water consumption	Use of water resources for domestic life and industrial production	*Productivity* of water resources	Current generations	Water consumption
Agricultural activities	Water consumption	Use of water resources for irrigation	*Productivity* of water resources	Current generations	Water consumption
Extreme rainfall	Flood risk	Loss of lives and damages of properties	*Resilience* to increasing flood risk and vulnerability of local communities	Current generations	Flood risk

Table 4.7 PAM for indicator selection for UGR's economic development

Impact Generators (IIGs/EIGs)	*Impact on*	*Issue*	*Concern*	*External Impact Receivers (EIRs)*	*Indicator*
Hydropower Development	Hydropower generation	Increasing electricity generation capacity, which boosts local economy	*Productivity* of water resources.	Current generations	Hydropower
Water utilities development	Water supply and sanitation	Sufficient financial capacity to improve and maintain water supply for agricultural, industrial and domestic uses.	*Productivity* of water resources	Current and future generations	Financial capacity
	Sanitation and wastewater management	Sufficient capacity for wastewater treatment.	*Sufficient access* to wastewater treatment facilities		Financial capacity
Tourist sites development	Economy	Boosting local economy	*Productivity* of water resources.	Current generation	Tourism
Agricultural activities	Food production	Poverty relief, increasing food security and income	*Productivity* of water resources	Current generation	Food production
Fishery	Food production	Poverty relief, increasing food security and income	*Productivity* of water resources	Current generation	Food production

Table 4.8 Sustainability indicators and indices for Upper Ganga River Basin

Sustainability Domains	Sustainability Indicators		Measurements
Environmental Performance (EP)	EP_1	Environmental Flow Indicator	Flow deviation in the Upper Ganges gauging station near Haridwar.
	EP_2	Water Quality Indicator	Water quality indicators BOD and DO at Haridwar section.
	EP_3	Forest Cover Indicator	Annual change in forest areas coverage in Uttarakhand.
	EP_4	Biodiversity Indicator	Density of benthic macro invertebrates and key fish species in the mainstream at Rishikesh section of Upper Ganga.
Social Wellbeing (SW)	SW_1	Water Consumption Indicator	Total water abstracted in Uttarakhand state.
	SW_2	Sanitation Coverage Indicator	Percentage of people with improved sanitation in Uttarakhand
	SW_3	Water Supply Indicator	Percentage of people with access to water supply in Uttarakhand
	SW_4	Flood Risk Indicator	Flood risks in terms of duration, frequency and flood volume.
Economic Development (ED)	ED_1	Hydropower Indicator	Hydropower generation capacity in Uttarakhand state.
	ED_2	Financial capacity	Annual GDP invested in water sector in Uttarakhand state.
	ED_3	Tourism indicator	Annual revenue generated by tourism in Uttarakhand state.
	ED_4	Food Production Indicator	Annual food production and fisheries in Uttarakhand state.

4.2.4 Verification of Indicator Set

Verification of the assessment framework was done through a roundtable discussion on “Integrated River Sustainability Assessment” at CEEW on 11 September 2013 (see Appendix III.4). Key stakeholders from CEEW, WWF India and PSI attended the discussion. Following a presentation on the sustainability assessment framework for the Upper Ganges and primary results, comments and feedback were received from stakeholders (see Table 4.9).

Table 4.9 Stakeholder’s options on the primary indicator set

Title Name	*Opinions*
Dr Arunabha Ghosh	The PAM methodology demonstrates a transparent approach for indicator selection. The assessment has addressed the main issues concerning sustainability of the Upper Ganges. One big challenge to this assessment is data availablitly. From the primary analysis, it shows that may data for the selected indicators are not available. I would suggest that replace some of the measurements/indicators based on data availability (Ghosh, pers comm., 2013).
Dr Nirmalya Choudhury	The framework has clearly set up the sustainability assessment framework the Upper Ganges. The indicator selection is holistic, whilst more sub-indicators can be introduced to make it more comprehensive (Choudhury, pers comm., 2013).
Rudresh Sugam	Uttarkhand state is used as the system boundary for the Upper Ganges in this assessment. This covers the majority of the Upper Ganga basin, yet there are a few districts under Uttarkhand state does not belong to the Upper Ganga basin. You need to justify how this affects the assessment result (Sugam, pers comm., 2013).
Dr Upali Amarasinghe	PAM represents a good methodology for generation indicators. It would be interesting to see how the results can be used for cross-

	basin comparison, as different indicators/crieteria were used (Amarasinghe, pers comm., 2013).
Dr Ravi Chopra*	A well-structured framework with clear thoughts and objectives. My concern is that this assessment is entirely based on second-hand data. Some of the data obtained from government reports, i.e. forest cover data, has poor credibility. For water quality data, there were insufficient data to show how it changes over the decade. Ideally, first-hand data should be collected and used for an independent assessment. I understand this is not practical. But the impacts of data quality on the assessment results needs to be addressed (Chopra, pers comm., 2013).

* Dr Ravi Chopra was not able to make the presentation. The work was sent to him and a brief interview was taken over the phone.

Based on stakeholders' feedback and data availability, the indicator set was updated, with some of the indicators (measurements) replaced by surrogates. These include the environmental flow indicator, water consumption indicator, water supply and financial capacity. These changes are shown in Table 4.10. A brief justification is given in the table where a surrogate measurement is used, and will be discussed in details in the next section.

Table 4.10 Sustainability indicators and indices for Upper Ganga River Basin

Sustainability Domains	Sustainability Indicators		Measurements	Changes made in respond to stakeholder’s comments
Environmental Performance (EP)	EP_1	Environmental Flow Indicator	Flow deviation in the Upper Ganges gauging station near Haridwar.	
	EP_2	Water Quality Indicator	Water quality indicators BOD and DO monitored at Haridwar section of Upper Ganga, 3 sets in a year.	
	EP_3	Forest Cover Indicator	Annual change in dense and open forest areas coverage in Uttarakhand	
	EP_4	Biodiversity Indicator	Density of benthic macro invertebrates and key fish species in the mainstream at Rishikesh section of Upper Ganga.	
Social Wellbeing (SW)	SW_1	Water Consumption Indicator	*Annual change in irrigated land areas. Due to the agriculture sector accounts for 94% of total water consumption, this is used as a surrogate to the water consumption.	Surrogate indicator is used due to unavailable water consumption data (Choudhury, pers comm., 2013).
	SW_2	Sanitation Coverage Indicator	Percentage of households with improved sanitation in Uttarakhand	
	SW_3	Water Supply Indicator	*Capacity of improved drinking water supply	Surrogate indicator is used to replace the measurement of water supply by the percentage of people with access to water supply in Uttarakhand (Amarasinghe, pers comm., 2013).
	SW_4	Flood Risk Indicator	*Variability of annual precipitation in Uttarakhand compared to 50 years' average annual precipitation in Uttarakchapel region.	Due to unavailable flow rate, precipitation indicator is used as a surrogate to the flood risk (Choudhury, pers comm., 2013).

Economic Development (ED)	ED_1	Hydropower Indicator	Hydropower generation capacity	
	ED_2	Financial capacity	*Annual GDP invested in Uttarakhand.	Due to data scarcity, surrogate indicator is used.
	ED_3	Tourism indicator	Annual revenue generated by tourism in Uttarakhand	
	ED_4	Food Production Indicator	Annual food production and fisheries in Uttarakhand	

4.3 Environmental Performance of UGR

4.3.1 Environmental Flow Indicator EP_1

The Environment Flow Indicator represents the flow regime of the river, and is determined by the departure of annual discharge from the long-term averages. Table 4.11 shows the long period (1951-2000) averages of river discharge of Ganges at Haridwar. If the annual flow in a particular year deviates by more than 33% from the normal, the environmental flow indicator is given a score of 0 for that year. If the annual discharge variability is within 33% of the normal, the score for that year is calculated from the following equation,

$$EP_{1,i} = 1 - 9 \times \left({Dep_i}/{Ave} \right)^2 \tag{4.1}$$

where $EP_{1,i}$ refers to the score of the environmental flow indicator for the given year i; Dep_i is the annual discharge (BCM) departure from normal; and Ave is the discharge normal (BCM) for the period of the past 50 years, which is 372.48 BCM.

Discharge data and results for the Environmental Flow Indicator are given as below.

Table 4.11 Discharge variability of Uttarkhand for the period from 2001 to 2010

Year	Discharge (BCM)	Departure from normal (BCM)	Percentage (%)	Score (0-1)
2001	378.86	6.38	1.71	1.00
2002	278.81	-93.67	-25.15	0.43
2003	424.06	51.58	13.85	0.83
2004	282.06	-90.42	-24.28	0.47
2005	284.41	-88.08	-23.65	0.50
2006	268.21	-104.27	-27.99	0.29
2007	351.88	-20.60	-5.53	0.97
2008	267.52	-104.96	-28.18	0.29
2009	232.98	-139.50	-37.45	0.00
2010	378.86	6.38	1.71	1.00

4.3.2 Water Quality Indicator EP_2

Water quality degradation is one of the most challenging issues of UGR. In this stretch of Ganges, serious problems of water quality and quantity have been recorded. Whereas in the middle reaches, i.e. downstream of Allahabad, once the Yamuna joins the Ganges, the quality and quantity improves.

The water quality indicator is determined by the Biochemical Oxygen Demand (BOD) and Dissolved Oxygen (DO) level monitored at Haridwar. According to the national standard, the water quality should reached Class B, the standard for outdoor bathing as listed in Table 4.12.

Table 4.12 National Water Quality Standard for Outdoor Bathing (Class B)

pH	6.5–8.5
Biochemical Oxygen Demand (BOD)	3 mg/l or less
Dissolved Oxygen (DO)	5 mg/l or more

Here we consider two sub-indicators, DO and BOD. If BOD reaches the standard, a score of 1 is given; if it exceeds 200% of the maximum value allowed by the standard, a score of 0 is given, in between the score is calculated by the percentile. For DO, if it reaches the standard value, a score of 1 is given, or else the score is calculated as the percentage of the standard value achieved. The final score of the water quality indicator is calculated from the following equation,

$$EP_{2,i} = 0.25 \times (DO_i + BOD_i)^2 \qquad (4.2)$$

where $EP_{2,i}$ refers to the score of the water quality indicator for the given year i; DO_i is the score for dissolve oxygen sub-indicator fo the given year i; and BOD_i is the score for biochemical oxygen demand sub-indicator for the given year i.

Raw water quality data and the results are presented in Table 4.13, showing a sharp decline in water quality since 2005.

Table 4.13 DO, BOD statistics and water quality indicator score

Year	DO	DO Score	BOD	BOD Score	Water Quality Score
2001	8.8	1	1.9	1.00	1.00
2002	8.5	1	2.0	1.00	1.00
2003	8.5	1	2.3	1.00	1.00
2004	7.7	1	2.8	1.00	1.00
2005	6.7	1	4.3	0.57	0.62
2006	8.7	1	4.1	0.63	0.66
2007	6.1	1	3.8	0.73	0.75
2008	6.7	1	5.6	0.13	0.32
2009	7	1	5.4	0.20	0.36
2010	7.2	1	5.8	0.07	0.29

4.3.3 Forest Cover Indicator EP_3

Forest cover accounts for over 60% of the land area in Uttarakhand. It is vital for the ecosystem, in terms of microclimate, water cycle, and biodiversity. The Nanda Devi National Park is one of the most spectacular wilderness areas in the Himalayas. It is dominated by the 7,800m peak of Nanda Devi, and is approached through the Rishi Ganges gorge, one of the deepest in the world (TERI, 2011). The forest cover indicator is decided by the amount of dense forest and open forest. According to the State's forest report, total forest cover in Uttarakhand has been maintained at the level of 60% throughout the past decade, and minor changes have been identified since 2003.

The forest cover indicator is determined by the percentage of dense forest, including very dense forest and moderate dense forest, in the total forest area. Scores of the indicator is calculated as follows,

If the percentage of dense forest is no more than 60%,

$$EP_{3,i} = 0 \qquad (4.3)$$

If the percentage of dense forest exceeds 60% but no more than 80%,

$$\mathrm{EP}_{3,\mathrm{i}} = 5 \times \left(\frac{\mathrm{F}_{\mathrm{den}}}{\mathrm{F}_{\mathrm{tot}}} - 0.6 \right) \qquad (4.4)$$

If the percentage of dense forest is more than 80%,

$$EP_{3,i} = 1 \qquad (4.5)$$

where $EP_{3,i}$ refers to the forest cover indicator score for the given year i; and F_{den} refers to the area of dense forest whilst F_{tot} is the total forest area.

Table 4.14 Uttarakhand forest cover statistics 2001 – 2011 (FSI, 2010)

(area in km^2)		2001	2003	2005	2007	2009	2011
Forest Categories	Very Dense		4002	4762	4762	4762	4762
	Moderate Dense	19023	14420	14170	14162	14165	14167
	Open	4915	6043	5561	5568	5568	5567
Total Forest		23938	24465	24493	24492	24495	24496
Scrub				272	271	271	271
Non forest				28717	28718	28717	28716
Percentage of dense forest		79.5%	75.3%	77.3%	77.3%	77.3%	77.3%
FCI Score		0.97	0.76	0.86	0.86	0.86	0.86

However, stakeholders found the data untrustworthy. Upali (2013) pointed out that the land areas in the report refer to areas were registered under different categories, which did not reflect the fact that land use had actually changed (Upali, pers comm., 2013). Intensive hydropower development in this area has led to considerable forest degradation. The development of dams, barrages and hydropower projects in

Uttarahand has generated great impacts on biodiversity in the Upper Ganges. We would therefore suggest GPS sensing for mapping local forest for future work.

4.3.4 Biodiversity Indicator EP_4

The biodiversity indicator is determined by the density of aquatic species in the mainstream at Rishikesh section of UGR. Survey data were obtained from the People Science Institute during a field trip in September 2013, covering vegetation structure, riparian vegetation, key bird species, livestock, algae, and key fish varieties.

The sequential comparison index (*SCI*) is used for biodiversity. SCI is a rapid method to estimate relative differences and to obtain numerical indicator of biological diversity in stream pollution studies (Cairns, 1968). This index represents the diversity and abundance of organisms in the monitored location. The biodiversity indicator score is calculated as,

$$EP_{4,i} = \frac{number\ of\ runs}{number\ of\ organism} \tag{4.6}$$

The procedure is to randomly arrange the organisms in your sample in a straight line, then begin at one end of the row of organisms and examine them one at a time (PSI, 2013b). If the organism appears similar to the previous one, continue on in the same *run*, if not, then count this as the start of a *run*. The more diverse a sample is, the higher the number of runs will occur. The SCI score ranges from 0 to 1, a score below 0.3 indicate poor water quality, according to WWF India reference value. The Biodiversity Indicator score is determined by the lowest SCI observed.

Table 4.11 shows the results of biodiversity assessment at Haridwar during the early half of the 2013. Five surveys were carried out by the People Science Institute, to examine the impacts of KUMBH 2013 on biodiversity in this section of river. However there were no survey data available for early years. These results could not show the effects of biodiversity conditions of past years, or predict changes over time. Slight changes shown are likely due to seasonal variation.

Table 4.15 Data on monitoring of benthic macro-invertebrates at Haridwar

Name of Species	Sampling Date				
	14/01/13	15/02/13	20/03/13	20/04/13	20/05/13
Damselfly (Lestidae)	-	-	-	-	-
Aquatic worm (Oligochaeta)	15	8	28	12	132
Molhuscs (Lymnaeidae)	116	62	10	72	40
Leech (Hirudidae)	59	19	41	-	-
Water penny (Psephenidae)	5	-	3	-	3
Blackfly larva (Simulidae)	-	12	-	-	-
Midge Larva (Chironomidae)	-	-	1	-	-
Diving Beetle	-	-	-	3	-
Total numbers of individuals	195	101	42	87	175
SCI	0.53	0.55	0.48	*0.24*	0.3

4.4 Social Wellbeing of UGR

4.4.1 Water Supply Indicator SW_1

Access to safe drinking water and decent sanitation is one of basic human needs, yet remains a big challenge to India nationwide. According to UNDP, over 90% of population has no access to adequate sanitation in India in 2000 (UNDP, 2006). The MDG for sanitation of 75% coverage has largely lagged behind (UNDP, 2000). In the social wellbeing domain, households' sanitation coverage and the percentage of population with access to safe drinking water are calculated, thus examining to what extent the utilities can meet the needs.

$$SW_{1,i} = {(C_i - C_{min})} \Big/ {(C_{max} - C_{min})} \qquad (4.7)$$

where $SW_{1,i}$ refers to water supply indicator score of the given year i; C_i is the coverage of safe drinking water supply in Uttarakhand Sate in year i; and C_{min} and C_{max} are the minimum and maximum coverage during year 2001 to 2012 respectively.

Table 4.16 Raw data and indicator score for the Water Supply Indicator

Year	Coverage (%)	Water Supply Indicator Score
2001	81	0.58
2002	83	0.63
2003	84	0.65
2004	86	0.70
2005	86	0.70
2006	87	0.73
2007	88	0.75
2008	88	0.75
2009	89	0.78
2010	91	0.83

4.4.2 Sanitation Indicator SW_2

The sanitation indicator is determined by the percentage of properties with an individual household latrine in Uttarakhand state. Access to sanitation has been largely improved during the past decade in India. This is mainly due to the Total Sanitation Campaign (WSP, 2010)which aims to motivate rural households to build toilet facilities and encourage their use. The score for the sanitation indicator is calculated by the cumulative achievement rate of the target (893301 households). The results shown in Table 4.13 indicate significant improvement in sanitation sector, yet more effects are needed to achieve full access.

Table 4.17 Sanitation development in Uttarakhand and indicator score

District/Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Almora	0	0	0	1766	2003	3601	2546	10308	12603	14781
Bageshwar	0	0	0	2122	2401	4554	3974	4215	4157	5302
Chamoli	0	0	0	1142	5892	6757	6348	6210	6548	8929
Champawat	0	0	0	1126	3880	4830	3659	2582	4383	3227
Dehradun	0	0	0	0	5790	918	8407	9338	9318	10821
Pauri Garhwal	0	0	0	5550	4170	4318	7355	9055	10819	13619
Haridwar	30	0	766	10702	1777	6254	11019	14268	14373	20359
Nainital	0	0	0	56	3512	4439	4554	3365	7554	6347
Pithoragarh	0	0	0	1980	4204	6508	5960	10213	10317	10439
Rudraprayag	0	0	0	2013	560	3235	5027	3039	4025	5307
Tehri Garhwal	0	0	0	0	10004	6718	9410	12626	12585	12249
Udhamsingh Nagar	0	0	0	1010	8667	7968	6980	7884	13360	14689
Uttarkashi	0	0	0	8357	4248	4851	2542	5781	5069	6844
Total	30	0	766	35824	57108	64951	77781	98884	115111	132913
SW_2 Score	0.00	0.00	0.00	0.04	0.10	0.18	0.26	0.38	0.50	0.65

4.4.3 Agricultural Water Consumption Indicator SW_3

The Water Consumption Indicator is determined by total water abstraction for human use. There are three main water consumption sectors, related to agricultural, domestic and industrial water uses. In the present research area, agricultural water use accounts for over 94% of total water abstraction. Due to lack of data on total water consumption, the agricultural water consumption is used as a surrogate measurement. The total water consumption agriculture is based on the assumption that water consumption per hectare remains the same. This is because agricultural actives, including the irrigation technology, major crops planted etc., have not been changed significantly (DANET, 2010). Therefore, the agricultural water consumption indicator is dertermined by net irrigated area in Uttarakhand, and is continuously rescaled by the following formula,

$$SW_{3,i} = {\left(IA_i - IA_{min}\right)} \Big/ {\left(IA_{max} - IA_{min}\right)} \tag{4.8}$$

where $SW_{3,i}$ refers to water consumption indicator score of the given year i; IA_i is the net irrigated area in Uttarakhand Sate in year i; and IA_{min} and IA_{max} are the minimum and maximum net irrigated area during year 2001 to 2010 respectively.

Table 4.18 Irrigated areas and water consumption indicator score **(DANET, 2010)**

Year	Net irrigated area (Thousand hectares)	Water Consumption Indicator Score (0-1)
2001	346	0.5
2002	341	0.75
2003	346	0.5
2004	345	0.55
2005	343	0.65
2006	345	0.55
2007	341	0.75

2008	340	0.8
2009	338	0.9
2010	336	1

4.4.4 Flood Risk Indicator SW_4

The Flood Risk Indicator is determined by the probability of extreme events. Rainfall is one of the major sources of renewable water resources in the Ganges. In the Upper Ganges river basin, the annual average rainfall varied hugely from 390 mm to 2000 mm with an average of 1100 mm, between 1951 and 2000. Despite its inter-annual variability, 80% of the rainfall occurs during the monsoon months, namely, between June and September. Wide fluctuations occur in the flow characteristics of the river course, due to the large temporal variations in precipitation. This further leads to high risk of extreme events in this region. In the absence of flow data, the rainfall variability indicator is selected as a surrogate to represent flood risks in the river course. This is based on that the occurrence of flood and extreme events/storms are closely correlated in Upper Ganges,

The Rainfall Variability Indicator is calculated by the precipitation departure from the long-term averages. This indicates whether the precipitation in a given year show large variation to the normal, and implies the likelihood of this region to suffer extreme events in that given year. Table 4.19 shows the long-period (1951-2000) averages of rainfall in Uttarakhand. If the rainfall in a particular year deviates by more than 25% from the normal, the environmental flow indicator is given a score of 0 for that year. If the rainfall variability is within 25% of the normal, the score for the given year is calculated from the following equation,

$$SW_{4,i} = 1 - 16 \times \left({Dep_i}/{Ave} \right)^2 \qquad (4.9)$$

where $SW_{4,i}$ refers to the score of the flood risk indicator for the given year i; Dep_i is the annual precipitation (mm) departure from normal; and Ave is the rainfall normal (mm) for the period of the past 50 years.

Rainfall data, calculation of the flood risk indicator and results are given in Table 4.19 and Table 4.20. It shows the correlation between the flood risk and climate uncertainty, which increases in the recent decade.

Table 4.19 Precipitation statistics for the period 1951-2000 for the Uttarakhand

Monthly Average (mm)		Seasonal Average (mm)	
Jan	52.1	Winter (Jan - Feb)	106.2
Feb	54.1		
Mar	57.6	Pre-Monsoon (Mar - May)	156.0
Apr	33.3		
May	65.1		
Jun	167.8	Monsoon (Jun - Sept)	1229.1
Jul	428.1		
Aug	426.3		
Sep	206.9		
Oct	58.6	Post-Monsoon (Jun - Dec)	89.6
Nov	9.7		
Dec	21.3		
		Annual	1580.9

(Source: Hydromet Division of India Meteorological Department)

Table 4.20 Rainfall variability and flood risk of Uttarkhand from 2001 to 2010

Year	Rainfall (mm)	Departure from normal (mm)	Percentage (%)	Score (0-1)
2001	1549.3	-31.6	-2.00	0.99
2002	1588.5	7.6	0.48	1.00
2003	1903.7	322.8	20.42	0.33
2004	1584.4	3.5	0.22	1.00

2005	1469.3	-111.6	-7.06	0.92
2006	1264.8	-316.1	-19.99	0.36
2007	1894.4	313.5	19.83	0.37
2008	1298.5	-282.4	-17.86	0.49
2009	1076	-504.9	-31.94	0.00
2010	1864.3	283.4	17.93	0.49

4.5 Economic Development of UGR

4.5.1 Hydropower Generation Indicator ED_1

With a potential of 20,000 MW, Uttarakhand state has the richest hydropower resources in the basin. Yet, It remains largely unexploited with only 3,124 MW of installed capacity so far (Pandey and Rai, 2009). According to NRSC (2013), only a third of the hydroelectric power potential of the Ganges river basin has been achieved under current scheme (India-WRIS, 2013). With the creation of the state in 2000, its hydropower potential was considered as a key supply to the northern grid of India, institutional policies were formulated to promote hydropower development through independent power producers.

Since mid-1990s, a total of 48 small-scale projects had been planned by the independent power producers with planned generation capacity of 2423 MW. However, only 10% of the projects with generation capacity of 418 MW were completed by 2009. Figure 4.4 shows the hydropower power projects in Upper Ganges river basin underway in 2009. The slow uptake of hydropower resource is mainly due to inadequate feasibility studies, land acquisition issues, absence of evaluation, monitoring, and regulation (Pandey and Rai, 2009). Hydropower generation is still dominated by medium and large hydropower projects with over 25 MW installed capacity.

Table 4.21 lists large hydropower projects in the Uttarakhand.

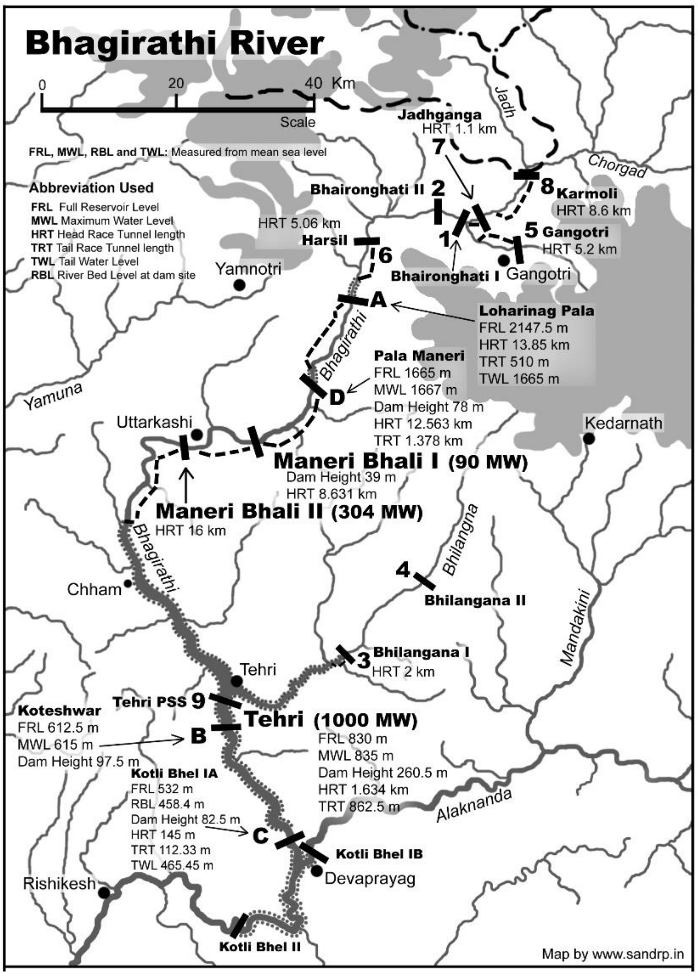


Figure 4.4 Hydropower projects in Uttarakhand in UGR (SNDRP, 2010)

Table 4.21 List of medium to large hydropower projects in Uttarakhand (India-WRIS, 2013)

Name	IC (MW)	Commission	Name	IC (MW)	Expected commission
Khatima	41	1956	Shrinagar	330	2015
Ramganga	198	1975	Phata Byung	76	2015
Garhwal Rishikesh Chilla	144	1981	Singoli Bhatwari	99	2015
Tanakpur	94	1992	Tapovan Vishnugad	520	2016

Dhauliganga	280	1999	Tehri PSS	1000	2017
Vishnuprayag	400	2006	Lata Tapovan	171	2018
Tehri	2000	2006	Vishnugad Pipalkoti	444	2018
Maneri Bhali Stage - II	304	2008			
Maneri Bhali State - I	90	2008			
Koteshwar	200	2011			

The hydropower indicator is hereby determined by the potential achieved,

$$ED_{1,i} = \frac{IC_i}{IC_{exp}} \tag{4.10}$$

where $ED_{1,i}$ corresponds a given year and IC refers to the installed capacity (MW) of major hydropower projects; and IC_{exp} refers to the expected total install capacity in 10 years' time. This assumption is based on the notion that the hydropower development plan at the time aims to meet the regional energy demand in a decade.

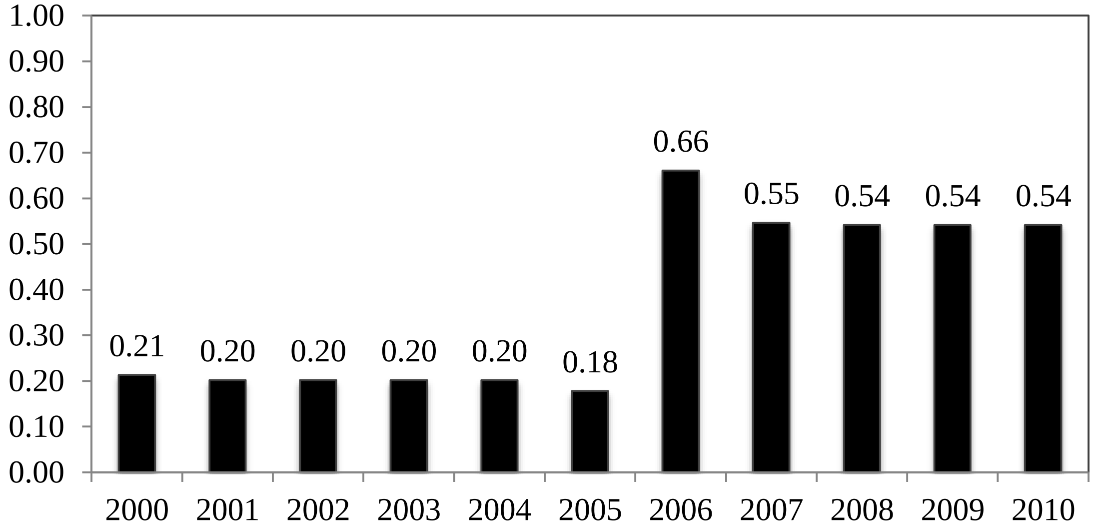


Figure 4.5 Hydropower Generation Indicator of UGR

Despite notable development in the latter half of the decade, hydropower projects in Uttarakhand are broadly criticised for being responsible for intensifying the magnitude of catastrophic floods in this area (Upali, pers comms., 2013)In absence of regulation and monitoring, small-scale hydro projects pose significant impacts on the floodplain, local forests and flow regime and river channel, which leads to environmental degradation and a decline in resilience. Nevertheless, considering the religious significance of the Upper reaches of Ganga, the changing appearance of the river course raises particular concerns on the cultural and aesthetic value of the river. It is suggested that a socio-political consensus needs to be reached before further promoting hydropower development in this region (SANDRP, 2008).

4.5.2 Financial Capacity ED_2

Sufficient financial capacity is crucial for integrated water resources management. Despite administration and monitoring expenses, large initial capital investment is required to improve water utilities, flood defence and hydropower projects. Also, funds are also needed for disaster relief, water-related education, public awareness campaigns, and institutional capacity building. The financial capacity indicator is determined by per capita financial input in water resources management. In the absence of state-wise data for Uttarakhand, the Financial Capacity Indicator is determined by per capita expenditure of the Minister of Water Resources in India, assuming a linear relationship between the state and the national dataset. The prosed expenditure of 2015, 2076.55 Rs. in crore, is set as the reference value of sustainability, according the 12th *Five Year Plan of MWR.*

$$ED_2 = \frac{Exp_i / Pop_i}{Exp_{12} / Pop_{12}} \tag{4.11}$$

where Exp_i is the expenditure of the given year i; and Pop_i refers to population of the given year i.

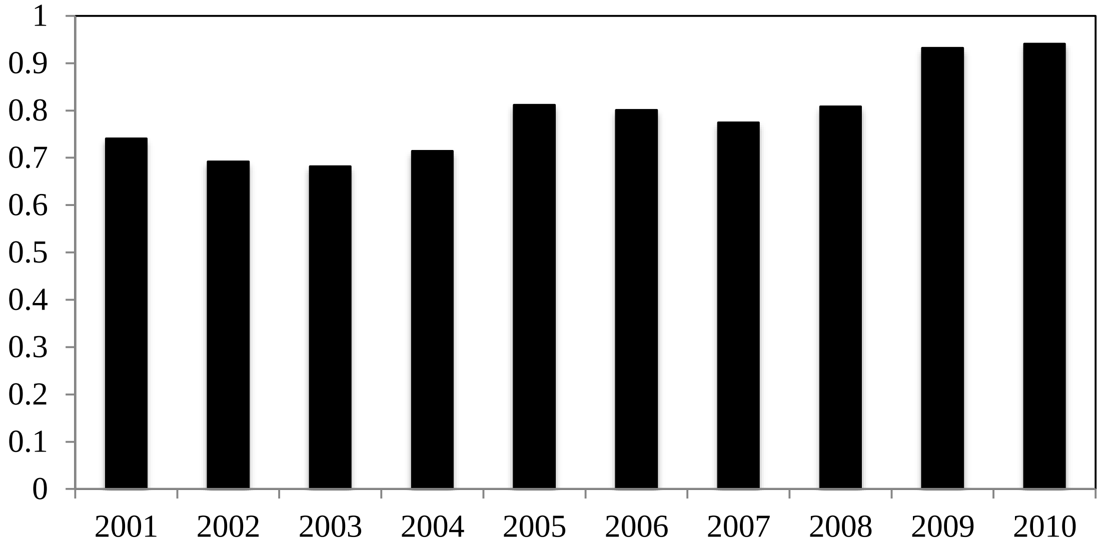


Figure 4.6 Financial Capacity Indicator of UGR

Table 4.22 Expenditure by Ministry of Water Resources in India

Organization/Schemes \ Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Secretariat-Economics Services	12.59	11.59	12.58	14.29	18.22	21.42	17.32	25.42	32.62	37.68
Major & Medium Irrigation	170.4	170.44	173.96	182.92	182.44	186.14	201	307.97	375.31	372.43
Minor Irrigation	154.84	139.05	131.73	134.07	130.03	134.79	109.49	142.61	181.56	191.51
C.A.D	148.13	152.16	144.02	142.76	199.9	191.6	277.84	0	0	0
Flood Control & Drainage	150.54	118.42	127.45	149.41	199.23	199.82	108.33	251.01	252.62	285.43
Transport Sector	34.49	45	47.12	53.82	52	48.87	53.91	85.6	107.64	84.56
Total	670.99	636.66	636.86	677.27	781.82	782.64	767.89	812.61	949.75	971.61
Population in million	1040	1056	1072	1089	1106	1122	1138	1154	1170	1186

Rs. In crore, 1 crore = 10 million

4.5.3 Tourism Indicator ED_3

The tourism indicator is determined by the number of domestic tourists and international tourists. Weightings were assigned to domestic tourism and international tourism as 0.9 and 0.1 respectively, according to their contribution to government revenue.

$$ED_{3,i} = 0.9 * {DT_i}/{DT_{max}} + 0.1 * {IT_i}/{IT_{max}} \tag{4.12}$$

where TI_irefers to tourism indicator score of the given year i; $DT_i$is the number of domestic tourists of the given year i; DT_{max} is the maximum number of domestic tourists during 2000 to 2010; $IT_i$is the number of international tourists of the given year i; and IT_{max} is the maximum number of domestic tourists during 2000 to 2010.

Table 4.23 Raw data and indicator score for the Tourism Indicator

	Tourism Indicator		Tourism Indicator Score
	Number of domestic tourists (in million)	Number of international tourists (in million)	
2001	10.37	0.06	0.35
2002	11.37	0.06	0.38
2003	12.58	0.06	0.42
2004	13.34	0.08	0.46
2005	15.92	0.09	0.55
2006	18.99	0.10	0.64
2007	19.77	0.10	0.67
2008	20.55	0.10	0.69
2009	21.93	0.11	0.74
2010	30.21	0.13	1.00

(GOI, 2008)

4.5.4 Food Production Indicator ED_4

The food production indicator is determined by two sub-indicators, the crop production and the fishery sub-indicators. The crop production sub-indicator represents the gross production of major crops in Uttarakhand, including food grain, oilseed and sugarcane. Food grain sub-indicators are calculated by the equation below. Other sub-indicators, namely, oilseeds and sugarcane are calculated in the same way.

$$\mathrm{FG_i} = \mathrm{FGP_i} / \mathrm{FGP_{max}} \tag{4.13}$$

where FG_i refers to the food grain score of the given year i; $FGP_i$is food grain production of the given year i; and FGP_{max} is the maximum food grain production during 2000 to 2012. The raw data and score for FGP is listed in Table 4.24.

To calculate the Crop Production sub-indicator, weightings are assigned to its different components, namely, 0.7 for food grain, 0.2 for oilseeds, and 0.1 for sugarcane. The weightings were given according to their contribution in total food production and importance to the economy (judged by empirical experiences). The Crop Production Indicator is calculated by.

$$\mathrm{CPI_i} = 0.7 \times FG_{\mathrm{i}} + 0.2 \times OS_{\mathrm{i}} + 0.1 \times SC_{\mathrm{i}} \tag{4.14}$$

where CPI_i refers to Crop Production Indicator score of the given year i; FG_i, OS_i, SC_i are the scores for food grain production, oilseed production and sugarcane production of the given year i respectively.

Table 4.24 Raw data and scores for the Crop Production Indicator (RBI, 2013)

Year	Crop Production sub-indicators

	Food Grain (10^3 tons)	Oilseed (10^3 tons)	Sugarcane (10^3 tons)	Crop Production Indicator Score
2001	1707.5	17.7	7555.3	0.89
2002	1559.1	23	7331.7	0.90
2003	1724	34	7651	0.85
2004	1761	38	6441	0.95
2005	1594	30	6134	0.95
2006	1735	21	6100	0.85
2007	1796	29	7686	0.88
2008	1765	26	5590	0.97
2009	1780	29	5058	0.89
2010	1818	23.4	6516	0.93

The fishery indicator is determined by GDP of the fishery sector in Uttarakhand.

$$\mathrm{FI_i} = {}^{\mathrm{F_i}}\!/\!_{\mathrm{F_{max}}} \tag{4.15}$$

where FI_i refers to Fishery Indicator score of the given year i; F_i is fishery revenue of the given year i; and F_{max} is the maximum fishery revenue during 2000 to 2012.

To calculate the final score of the Food Production Indicator, weightings are assigned to different indicators according to their percentages in total food production, and importance to the economy (judged by empirical experiences). Values 0.7 and 0.3 are assigned to the Food Production Indicator and the Fishery Indicator respectively. The final score of the food production is calculated from,

$$\mathrm{ED_{4,i}} = 0.7 \times \mathrm{CPI_i} + 0.3 \times \mathrm{FI_i} \tag{4.16}$$

The final results of food production indicator are presented in Table 4.25, show general growth in flood production with slight variations.

Table 4.25 Fishery, Crop Production and Food Production Indicators

Year	Fishing (Figures are in Rs. Lakh)	Fishery Indicator Score	Crop Production Indicator	Food Production Indicator
2001	647	0.33	0.89	0.722
2002	688	0.39	0.9	0.747
2003	689	0.39	0.85	0.712
2004	803	0.54	0.95	0.827
2005	787	0.52	0.95	0.821
2006	930	0.71	0.85	0.808
2007	955	0.75	0.88	0.841
2008	960	0.75	0.97	0.904
2009	990	0.79	0.89	0.86
2010	1083	0.92	0.93	0.927

4.6 Results and Discussion

4.6.1 Assessment Results

Figure 4.7 shows the four indicators concerning the environmental performance category of the UGR. Increasing uncertainty of climate has been identified, based on large deviation of discharge and precipitation in this region comparing to the long-term average. The water quality has been declining over the 10-year period, due to fast socio-economic development, increasing discharge of wastes but lack of wastewater treatment capacity. The forest cover rate remains steady according to the statistics published by the local government. Yet, it was criticized as ”hiding the truth” by Chopra (2013), who claimed that potential hydropower development poses a significant threat to local forests and deforestation is one of the emerging challenges for Upper Ganges.

The social wellbeing results in Figure 4.8 show that gradual progress has been made towards improved water consumption, sanitation coverage and drinking water supply. Major improvements in both water supply and sanitation have been identified. This is largely due to

WASH campaigns widely carried out nationwide in India since 2000. Risk perception towards flooding has increased significantly, due to frequent extreme events in the latter half of the decade. Due to insufficient data to reveal the climate pattern or long-term trend, the trend of flood risks remains unknown. Yet, many concerns were raised during stakeholder interviews, that man-made factors, such as deforestation, social settlements and infrastructure development in flood-prone areas, lead to increasing vulnerability to extreme events. To support, it is worth mentioning that two extreme events occurred in the summers of 2011 and 2013. The 2011 flood caused 115 deaths (Pradhan, 2011), and the number of fatalities of the 2013 flood was estimated over 5000 (Lucknow, 2013). Immediate actions are required from the government to alleviate flood risk in UGR.

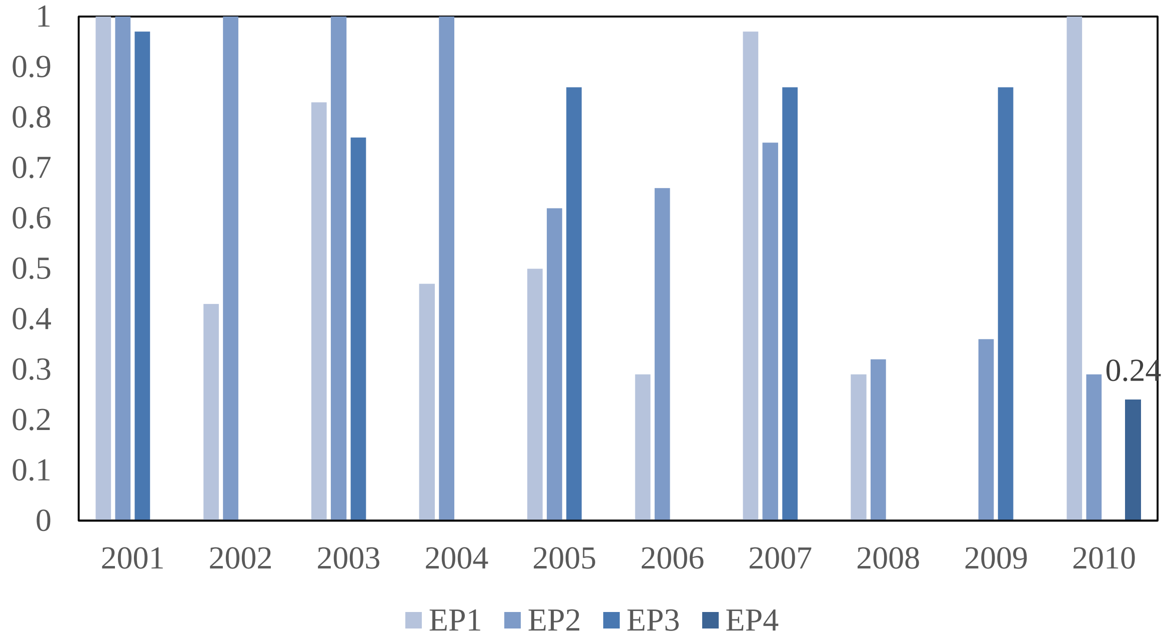


Figure 4.7 Environmental Performance of UGR

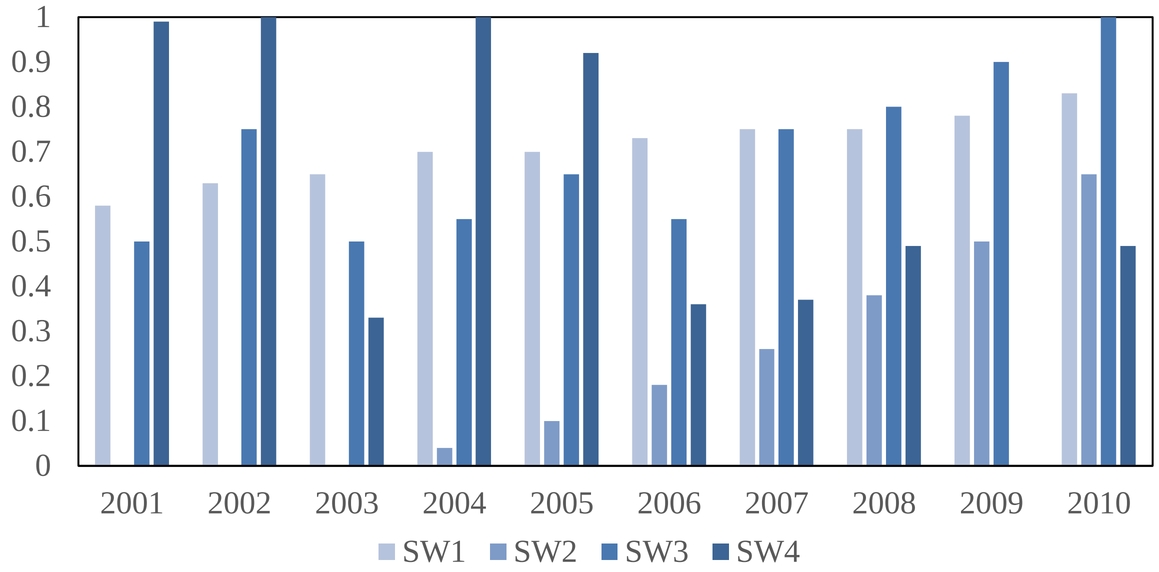


Figure 4.8 Social Wellbeing of UGB

For the economic development domain, all indicators show steady improvement. Yet, an indicator measuring infrastructure capacity for flood defence and/or water storage capacity is neglected. It is recommended that future work should include such an indicator that incorporates the infrastructure capacity for managing water-related risks in the economic development domain.

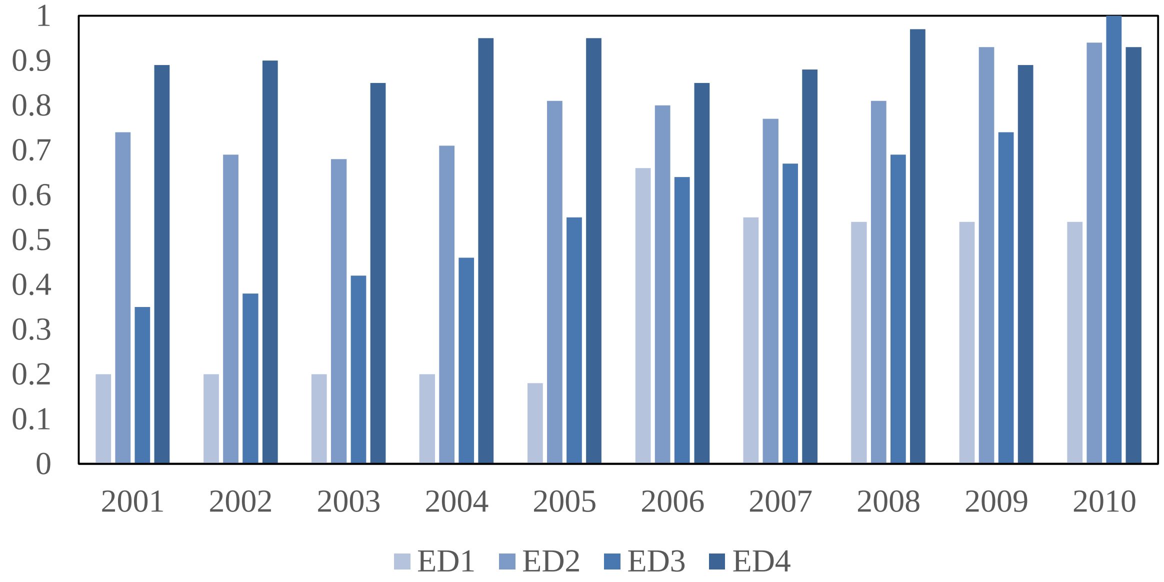


Figure 4.9 Economic Development of UGR

4.6.1 Composite Sustainability Indices

Composite sustainability indices, *EPI*, *SWI* and *EDI* are calculated in the same way comparing to the Yellow River case study. The equation for *EPI* is as below,

$$EPI_i = \sum_{j=1}^{n} EP_{j,i} / n \qquad (4.17)$$

where EP_i is integrated environmental performance score of the given year *i*; $EP_{j,i}$ refers to the normalized score of the j^{th} indicator in the environmental performance domain for the given year *i*; and *n* is the number of available indicators in the environmental performance domain in that given year.

Composite indices for three domains are calculated and shown in Figure 4.10. It indicates variations of EPI responding to climate uncertainty and steady growth in SWI and EDI.

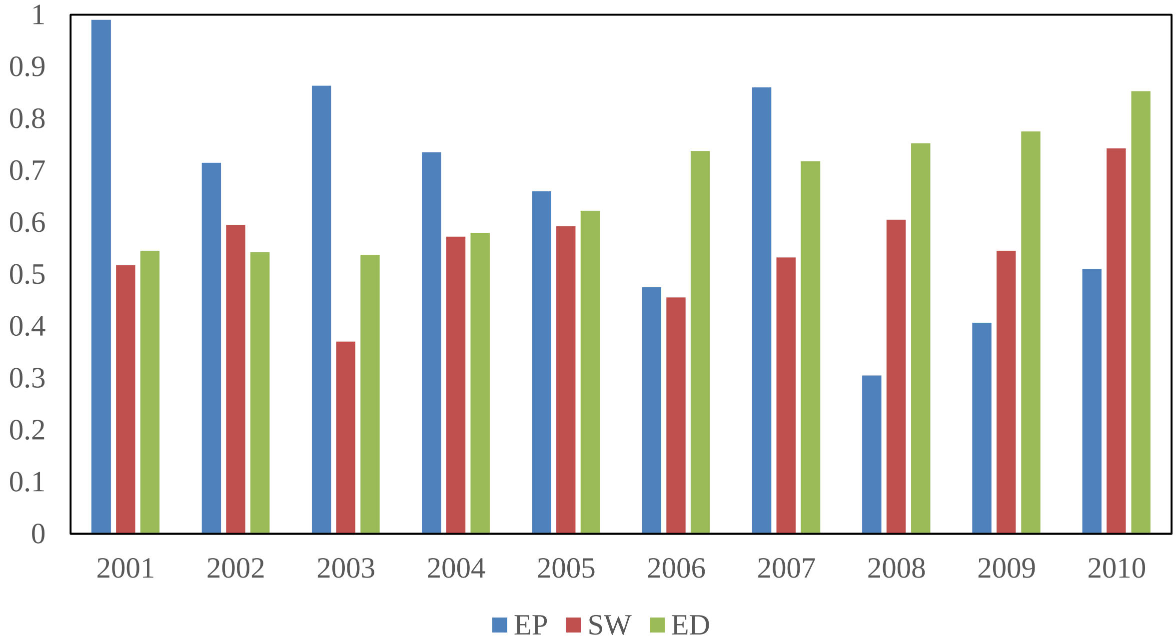


Figure 4.10 Composite Sustainability Indices for the Ganges

CHAPTER 5. Critical Review and Comparative Analysis

This chapter presents critical self-evaluation of the case studies, and comparative discussions on sustainability of the Yellow River and the Ganges. It also discusses the following topics, usefulness of indicators and indices in the light of data issues, distinctive management regimes of the two river basins, selection of indicators for specific sustainability concerns.

5.1 Critical Review

5.1.1 Yellow River Case Study

Stakeholder bias may occur due to various reasons, including education background, knowledge structure, personal experiences, political interests etc. During stakeholder interviews, stakeholders in general have very good knowledge about the Yellow River and river basin management from their work experiences, and were able to provide their insights into river sustainability and integrated river basin management. However, we observed that stakeholders tend to focus on the fields in which they have the most knowledge and experience. As the interview was semi-structured, they tend to spend much more time on questions they’re familiar with, and they were very likely to suggest that their focus area generates the most pressing sustainability concerns for the Yellow River.

Before conducting fieldwork, no consideration was given to this. Possible measures should have been taken to minimise the bias. Yet, our consultation process has engaged a broad range of stakeholders from multi-disciplinary areas. The final indicators selection is made through PAM using key information gained from the stakeholder interviews, rather than voted by the stakeholders. Based on that, it is believed that stakeholders' bias have no significant impacts on the final assessment framework for the Yellow River.

Another issue with stakeholder interviews is inadequate documentation. During the fieldwork, stakeholder's interviews were not recorded or transcribed after. Although intensive notes were taken, with key information summarized and translated into English shortly after each interview, some information may be neglected during intensive conversations. Due to no recording of the interviews, the researcher was unable to review those interviews. This may result in loss of some useful information.

In order to provide a holistic review, sustainability assessment of a large river basin requires large quantities of data. During our research, concerns were raised about data availability and data quality. This presents the biggest challenge to the assessment. There are two concerns with data availability, whether such the data we need exists, and whether we can have access to the data. For instance, biodiversity data was only available in three years, and no such data was available before 1980s. It is difficult to generate a temporal trend of biodiversity based on three sets of data, or to compare the current status of biodiversity with half a century ago. With regard to the financial capacity indicator, we cannot get data as the total financial input in managing the Yellow River. A surrogate indicator was chosen as an alternative, based on data availability. Although a surrogate indicator can be very useful in the absence of required data, it cannot measure the specific concerns captured by the original indicator. Therefore, the use of a surrogate indicator reduces the strength of the assessment result.

The concerns with data quality are associated with consistency, accuracy, relevance, timeliness with the date set etc. For instance, raw hydrological data in terms of daily discharge of LYR and sediment load during 1949 to 1997 was obtained from PKU. Alternative data from a different source has to be used to cover the period from 1997 to 2010. Although measures have been taken to reduce the impacts, this may still affect consistency of the final indicator value. For the public health indicator, it was intended to be measured by the number of people affected by water contamination incidents in a given year. However, the only data we found relevant was the number of water contamination incidents occurred in a given year. Although it gives information on frequency of such an incident, the extent to which people are affected remains unknown.

5.1.2 Ganges Case Study

A few weaknesses were identified with regard to the system boundary, stakeholder's interviews and data quality. First, the temporal boundary was set as from 2001 to 2010, due to limited data availability. This was insufficient to understand either environmental flow, climate patterns, or the long-term climate trend. From this short period, it would be difficult to gain accurate understanding towards the flows characters and flood risks. In addition, this temporal scale is no broad enough to cover intergenerational effects, so the assessment results were unable to reflect intergenerational changes towards sustainability.

Second, stakeholder's interviews were not thoroughly documented. During the field trip, the stakeholder's interviews were not recorded or transcribed. Although intensive notes were taken, with key information summarized, the researcher was unable to review the original interview upon back from the field trip. This may result in loss of some important information.

Third, issues with data availability and data quality hinder the implementation of the assessment framework. The concern about temporal scale discussed above is mainly due to limited data availability. According to PAM, the indicator set was selected by reviewing the complex river system, not by availability of data that can be obtained. Therefore, some of the indicators selected had no data available for carrying out calculation. Based on the data we obtained, surrogate indicators were selected to replace the original measurements. This is helpful in completing the assessment. Nevertheless, the surrogates cannot measure exactly what the framework was designed to measure. The accuracy and usefulness of the final assessment results were consequently reduced.

Data credibility is another issue, which was identified during stakeholder consultation. Chopra commented on the forest cover data gained from government reports: “Although there was little change shown in the forest coverage for the ten years’ period, deforestation in Upper Ganges was a severe issue based on observations of the forest areas” (Chopra, pers comms., 2013). Chopra further suggested that first-hand data should be collected and used where possible, for instance, water quality data and flow rate. This would be the most efficient approach to counter data issues, but at this stage, it seems not practical due to limited capacity and funding.

5.1.3 Indicator and Composite Indices

Due to data issues discussed above, concerns were raised about the usefulness of indicators and composite sustainability indices. PAM methodology presents an attempt to develop a holistic set of sustainability indicators from an independent and comprehensive review. In the light of surrogates and data gaps, it is helpful in terms of identifying knowledge gaps and what is needed to be measured. With a surrogate, the indicator still gives some information on the issue which PAM aims to tackle.

A single indicator with poor data availability, or replaced by a surrogate in the case of no data, the accuracy and usefulness of the indicator was reduced. This is because it cannot provide a precise assessment for the issue/impact identified through PAM. The strength of PAM is that, all the indicators are independent from each other, interconnections are minimized in the process of indicator selection. Therefore, these “weak” indicators will not affect other “strong” indicators, which has good data. As for policy-maker with a specific need, they may still refer to some of the indicators for useful information they need. Further, a selected group of indicators can be compiled into a composite index to measure specific concern (discussed in section 3.6.2). This is particular useful for understanding performance of one specific area, for instance, water utilities index for LYR.

With regard to composite sustainability indices for environmental performance, social wellbeing and economic development, strength of these indices were affected by some of the “weak” indicators applied. Nevertheless, the uncertainty introduced by those “weak” indicators may have limited impacts on the long-term, due to the aggregation process may have averaged out the extremes. It is suggested that in future work, weightings can be applied to different indicators to test robustness and sensitivity of the composite indices.

Besides, it is suggested that an indicator with inadequate data to support it should not be used in a specific assessment. For instance, in the Yellow River case study, a potential water risk index could be constructed by combining the flood risk indicator, drought risk indicator and the public health indicator to provide specific information on water related risks and vulnerability. However, inadequate public health data, leading to the use of a surrogate indicator, would add misleading information to the potential risk index and generate significant impacts on the final assessment result. Therefore, we would recommend to rely on the information provided by strong individual indicators, rather than unnecessary combination in this case.

5.1.4 Reflection and Evaluation of the Final Indicator Sets

Despite the weaknesses discussed above, the final indicator sets for the two river basins still present a well-thought-through and holistic framework for measuring river sustainability. It advances the use of composite indices by overcoming a few conceptual and practical issues identified in section 1.3.3.

For the Yellow River, a set of 18 indicators was selected through PAM and categorized under three domains of sustainability. The assessment focuses the attention on the Lower Yellow River basin, due to the fact that most of the existing and emerging issues were found in the lower reaches of the river. Comparing to previous composite indices for measuring water resources i.e. WPI, this framework has been improved in the following ways: firstly, a comprehensive working definition of river sustainability was developed and used to guide the assessment. This responses to the concern raised by Chenoweth (2008) that a composite index for measuring a vaguely defined terms may fail to provide adequate measures. Secondly, instead of measuring sustainability of the entire river basin, the assessment focuses attention on the lower reaches of the Yellow River, which have the same geographical and socio-economic conditions. This captures the unique and emerging issues within the boundary. Furthermore, the final results are not given in a single index, instead, they are presented in three indices referring to three domains of sustainability. In this way, the assessment provides more sensible and meaningful information by showing the interactions of the environment, society and economy.

Similarly, a set of 12 indicators is selected for measuring sustainability of the Upper Ganges River basin. The tailored set responses to the major concerns with the river. Comparing to the Yellow River case study, a slightly different set of indicators was selected for the Ganges. This is because through literature review and stakeholder consultation, different sustainability concerns and different needs for development were identified. This proves PAM as an independent review process, as well as a participatory and transparent method.

5.2 Comparative Analysis

5.2.1 Comparative analysis of River Sustainability

Tailored indicator sets were developed for these two river basins based on PAM. Different indicators and metrics were selected. This is not only because these two rivers have distinctive characteristics, but also due to the fact that river sustainability is interpreted from different sustainability perspectives. In the context of water scarcity, integrated management of LYR concerns *sufficient* water resources, *fair* allocation of water resources between the ecosystem and human uses, and *resilience* in the community to cope with the changing climate. Sustainable development of UGR focuses on *access* to water and sanitation utilities, *productive* use of water resources, and *resilience* in the context of extreme events.

It is therefore difficult to conduct a sensible quantitative comparison between the two case studies. In light of different sustainability perspectives, different indicator sets associated with different metrics, normalization methods were used. Besides, due to insufficient data for

UGR, the two case studies cover a different temporal scale. This makes the comparison of sustainability trends over time even more difficult.

However, a qualitative analysis and comparison between the two river basins still provides us with meaningful information on the progress towards sustainability and IWRM. This is because the core concept of sustainability is about meeting needs: "…meet the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland et al., 1987). Different indicator set reflects different needs identified in LYR and UGR through our case studies. Therefore, instead of literally comparing the mutual indicators, what matters most to our assessment is whether these needs have been met from a basin's perspective. A qualitative comparison of the three domains can inform us the general trends of sustainability over the period of time, and helps identify the trade-offs, knowledge gaps and room for improvement.

Figure 5.1 shows evolvement of the sustainability triangle of the LYR from 1950s to 2000s. Integrated indices of the three domains were averaged by decades. The shifting of sustainability triangle from 1970s to 1990s shows clearly the trade-offs between environmental performance and economic development. This captures the casual relations between the three domains, and a balanced growth of the triangle suggests progress towards overall sustainability.

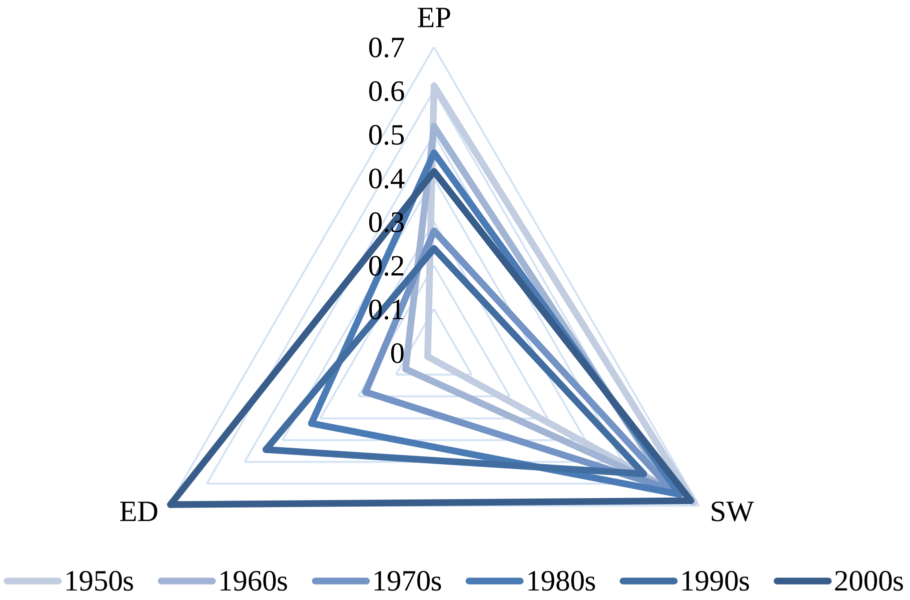


Figure 5.1 Sustainability triangle of LYR from 1950s to 2000s

Comparing to Figure 3.33, the sustainability triangle as shown in Figure 5.1 move the attention away from literal comparisons of the index scores. Instead, it provides simplified information in a more communicative way by highlighting the long-term trend of river sustainability (total area of the triangle) and the trade-offs in between the three domains (the shifts in the triangle).

Figure 5.2 and Figure 5.3 compares sustainability performance of LYR and UGR from 2001 to 2010. The Environmental Performance Indices shows that, after experiencing the extreme drought, pollution and river channel deposition, the environmental performance of LYR gradually improved from the worst situation (which occurred in 1997), following the YRCC’s efforts towards water and sediment regulation and river health restoration. Environmental performance of UGR, however, shows continuous variation mainly due to increasing uncertainty in precipitation, occurrence of extreme flooding events, as well as excessive wastewater discharge of poor water quality. Note that due to different indicators combined, this does not enable a literal comparison: for instance, a score of 0.74 for EPI of UGR in 2010 does not necessary mean a higher environmental sustainability grade than the EPI with a score of 0.69 for LYR. Integrated social wellbeing and economic development scores have been improved over the period of time for both river basins. (UNDP, 2013). For the LYR, the performance in terms of social-wellbeing and economic development had already reached a good status in 2001, and remained steady since. Whilst UGR is catching up fast, but still has a long way before reaching sustainability status in all three domains.

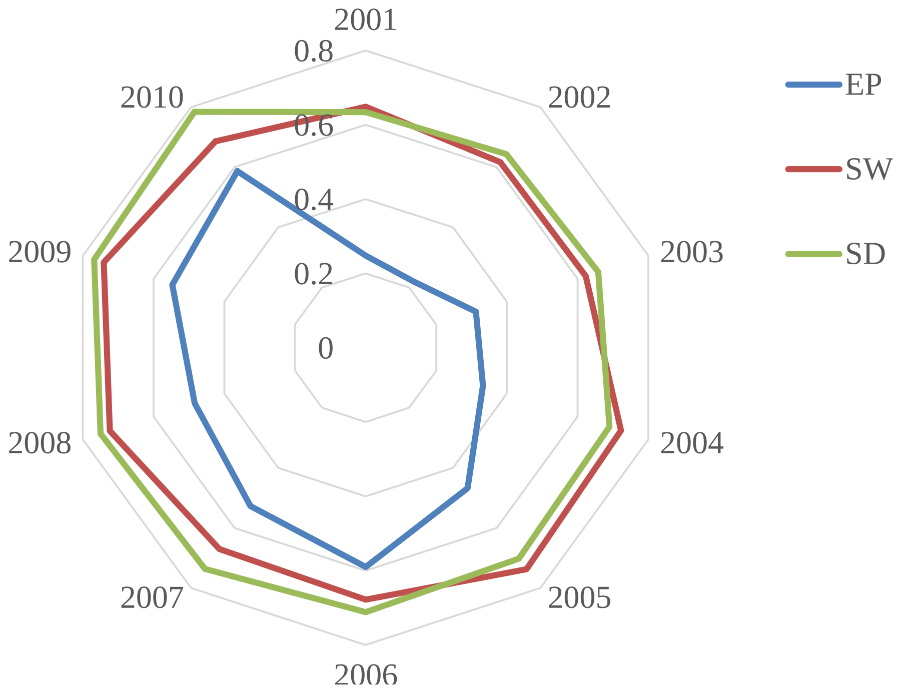


Figure 5.2 Sustainability performance of LYR from 2001 to 2010

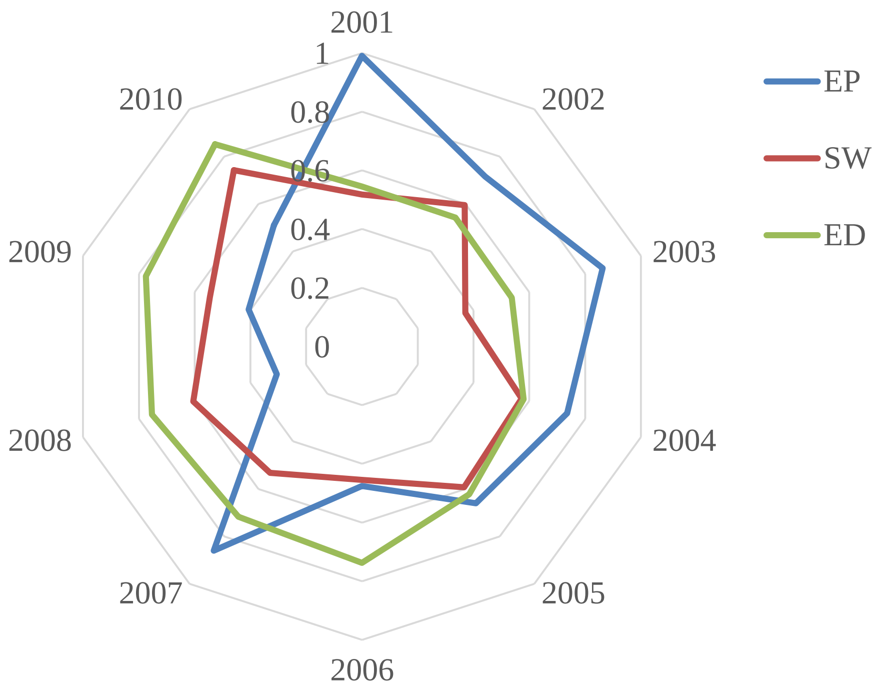


Figure 5.3 Sustainability performance of UGR from 2001 to 2010

5.2.2 Reflection and Evaluation

Regarding the two case studies, LYR and UGR are facing similar challenges in terms of population growth associated with fast urbanization, competing demand for water, and increasing risks of climate change. One major issue for both basins is water quality degradation. For the LYR, wastewater treatment utilities had been largely developed in 1990s. Meanwhile, the YRCC strengthened its regulations for industrial effluent. A more comprehensive water quality monitoring guideline was enacted in 2002. UGR also witnessed fast development of wastewater treatment utilities; yet, a comprehensive regulatory regime is absent. From the field trip, it is found that NGOs (i.e. WWF, PSI) have been collecting water quality and biodiversity data in the UGR. There appears to be a lack of government effort however.

As a result of climate change, LYR suffers from water scarcity whilst UGR faces increasing flooding risks. This raises the concerns on *resilience* for both basins. After the serious droughts in late 1990s, the YRCC reinforced its water allocation plan across the entire basin. In addition, multi-functional infrastructures have been built to regulate water and sediment. These efforts have proved to be effective in promoting efficiency and equity in the use of water. For UGR, the community has become increasingly vulnerable to flooding due to insufficient flood defence and poor regulation of small hydropower projects that interrupt the river course. The government should take immediate actions for climate change adaptation, incorporating infrastructures (flood defences, reservoir), early warning system and policies (i.e. make space for water).

In general, the LYR has a higher degree of sustainability compared to UGR, whilst UGR is developing at a faster pace. This is based on the fact that the overall socioeconomic situation was much better in the LYR than UGB in 2001, referring to HDI. Through the qualitative analysis, a trade-off between environmental capital and socioeconomic capital can be identified for the UGR. With fast expansion of hydropower projects, social settlement in flood-prone areas, communities at UGR became more vulnerable to flood risk and water contamination. The managers of LYR have learned from the crisis in 1990s, and established a more integrated regime to regulate the water and manage water related risks with long-term perspectives.

China and India are the two biggest rising economic powers in the world, each with populations of more than 1 billion people. Over the next decade, both countries are expected to maintain an 8 to 9% rate of economic growth (WB, 2010). In the 21st century, they will play a significant role in achieving the MDGs and shaping the environmental outcomes of the world (Bawa et al., 2010). However, fundamental differences in their political regimes are reflected in their approaches to manage the environment and natural resources. In China, the central government has the dominant control and responsibility for land, water, and other natural resources. Under a federal democratic system, the management of water resources in India is largely in the hands of the state governments (Aper, 2013). Nevertheless, from the two case studies, good practices towards integrated river basin management were identified, regardless of political regimes. These key elements will be discussed the next section.

5.3 Summary of Key Elements for IRBM

Rivers stand at the center of emerging challenges in terms of water security, economic development, energy generation and food production, as well as climate change. Therefore, the management of river basins needs to recognize and incorporate broader objectives and long-term perspectives. The evolution of IRBM addresses the need for a coherent multidisciplinary regime to manage basin water resources and their users in order to identify and to meet environmental and socioeconomic demands. River sustainability assessment not only monitors how the river is performing in order to achieve externally set objectives, but more importantly, it helps identify emerging issues and knowledge gaps, further provides a series of guidelines for integrated river basin management.

In response to competing economic, social and ecological goals, river basin management regimes have been developed across the world to meet local needs in tne context of increasing complexity. Based on the UNESCO WWAP, good river basin management should follow the follow principles (Ota, 2009),

- Develop a comprehensive understanding of the entire river system.

- Select the planning approach to suit the local conditions.
- Develop relevant and consistent plans under a theme.
- Prioritize issues for immediate attention.
- Adopt a phased approach to achieve long-term goals.
- Enable adaptation to changing circumstances i.e. climate.
- Engage stakeholders to strengthen institutional relationships and capacity.

The comparison of LYR and UGR shows significant differences in terms of institutional capacity towards IRBM. In the context of a decentralized government, it is more challenging for India to undertake integrated planning and respond to competing needs. During the field trip, we identified that UGR is managed through a 'bottom-up' approach, which largely depends local authorities and NGOs. This approach works well in terms of addressing local issues and needs; however, it lacks the capacity to meet the long-term needs, nor to balance the competing interests at basin level. Institutional capacity is weak in this case in terms of making integrated, long-term planning. In practice, UGR is increasingly vulnerable as local authorities can hardly develop a comprehensive, long-term flood management scheme. The management of LYR, on the contrary, is much more centralized and through a 'top-down' approach. YRCC plays the dominant role in terms of water sediment regulation, pollution control infrastructure development and alleviation of water-related risks, showing greater capacity to cope with increasing uncertainty and risks. Yet, policy development by using the 'top-down' approach needs to be carefully reviewed and must engage a broad range of stakeholders. This is to avoid arbitrary decision-making, which may result in irrelevant policy, or costly but unnecessary infrastructures.

Despite different characteristics of the river basins studied and the distinctive management regimes they operate, the present work has identified the following key elements for IRBM:

Comprehensive Knowledge

The river managers should have comprehensive understanding of the major river functions including hydrology, ecosystem, and socioeconomic activities, interactions and competing demands between these functions.

Institutional Capacity

Policy makers should also have the capacity to identify emerging issues associated with the river basin, further to develop policy in response to these issues. In the face of competing demand from different domains, sustainable river basin management allows trade-offs between alternative economic, social and environmental objectives, and between existing and potential future demands. Policy-makers should have long-term perspective and capacity to make optimized plans through multi-criteria decision-making.

Stakeholder Engagement

Broad participation of stakeholders is essential for IRBM. This is because a core value of sustainability is *meeting the needs* (Brundtland et al., 1987) and the engagement of stakeholders contributes to identifying the needs. Business and industries, scientific community, NGOs, and farmers all play an important role. Stakeholders further help strengthen institutional and financial capacity, develop technically sound and feasible plans, invest in water utilities and infrastructures, and monitor the policy implementation.

Resilience

IRBM policies should be resilient to foreseeable extreme weather, other risks and uncertainty. By assessing the sustainability performance of the river under different scenarios (i.e. hydrological, climate and socio-economic), this can help identify gaps in the current policy and underpin policies from a futuristic perspective. This is becoming increasingly important, as the impacts of climate change have shifted the policy priorities from mitigation towards adaptation.

Transparency

Transparent planning process is essential for IRBM, which engages stakeholders at all stages. Also, it is important for stakeholders to have access to transparent, reliable and update-to-date information concerning the river basin. This enables researchers and water managers to develop a sound, holistic assessment of the river basin, which helps monitor the complex and rapidly changing nature of river. This also contributes to identifying knowledge gaps and emerging concerns, and tracks the progress towards sustainability.

Community Capacity Building

It is essential to raise public awareness towards the magnitude of the water challenge and the increasing uncertainty and vulnerability through education and advocacy campaigns. This conceptual approach has proven effective, particularly for water conservation and demand management. Moreover, when facing of an emergency such as flooding or water contamination, rapid response and action from the community can reduce socioeconomic losses.

Accountability

IRBM reflects the accountability of a government towards water security. Water security concerns with both fulfil the productive potential of water and limiting its destructive impacts (Grey and Sadoff, 2007), which has been a priority to achieve sustainable development.

CHAPTER 6. Conclusion and Future Work

This chapter presents final reflections on the research into the river sustainability, comparing two large river basins, the Yellow River and the Ganges. Based on the case studies and discussion, this chapter provides a conclusion of the entire research project and a series of suggestions for future work.

6.1 Conclusions

This thesis investigated the use of sustainability indicators for integrated assessment of a large river basin. The concept of river health, often aimed towards a biologically pristine condition of a river, has been extended in this thesis to incorporate the river system's interconnected physical, biological and socio-economic functions. Based on the Brundtland Report, river sustainability has been interpreted as the *development of water resources in the river basin to meet the needs of the present generation without compromising the ability of future generations to meet their own needs.* Five perspectives have been identified to describe sustainability of river system, namely:

- The river should have *sufficient* runoff of required quality to maintain the ecological health of the river while also supporting social settlements and economic activities within the river basin.
- The river should be *resilient,* with the capacity to respond to a perturbation or disturbance by resisting damage and recovering quickly.
- Communities should have reasonable *access* to the services provided by the river, such as water utilities, recreation and transportation.

- The water resources should be used in a *productive* and efficient manner to provide socioeconomic development.
- Intra-generational *equity* requires the benefits and dis-benefits should be *fairly* distributed among the various stakeholders, while inter-generational equity requires that renewable water resources should not degrade or diminish with time.

Such perspectives help gain a comprehensive understanding of river sustainability. They are used for identifying impacts on sustainability and addressing impact generators, further for setting benchmarks, and for identifying appropriate targets to improve sustainability.

PAM has been employed in order to provide the guidelines for developing the sustainability assessment framework. As a participatory approach, PAM engages stakeholders at different stages of the assessment, who contribute to uncovering emerging issues and focusing attention on impact generators. Through a systematic process, a tailored indicator set has been selected and categorized under three domains of sustainability, namely, environmental performance, social wellbeing, and economic development.

Two case studies were undertaken to examine the underlying sustainability of the Lower Yellow River and Upper Ganges. Extensive fieldwork was carried out in China and India, in order to conduct stakeholder interviews and collect comprehensive data sets. For the LYR case study, raw hydrological data, sediment load data and socio-economic statistics were collected from PKU, YRCC, authoritative publications and database, whilst data for UGR case study were collected from CEEW, PSI and published literature. The data were then processed, and normalized scores for each indicator calculated. The score of each indicator for a given year was normalized to a score ranging between 0 to 1, where 0 refers to poor sustainability performance, which can be interpreted as insufficient resources, high uncertainty in climate, poor water quality, high vulnerability, etc., whereas 1 refers to good performance in terms of environment quality, resources efficiency, and management capacity.

The results show that, although social wellbeing and economic status for LYR have progressively improved since 1950, environmental quality declined in the latter half of 20th century, with the lowest point occurring in 1997 when extreme drought occurred. YRCC implemented measures to improve the river health by multifunctional infrastructure projects and water allocation regulation. This effort proved to be effective, as the general sustainability performance subsequently improved. The UGR study also identifies the trade-off between environmental capital and socioeconomic capital. With vast expansion of hydropower projects and new settlement in flood-prone areas, communities at UGR are increasingly vulnerable to extreme events. However, the local authorities manage the UGR presently lacks capacity for integrated planning. It is likely that the environmental performance of the UGR will continue to decline, particularly with increasing uncertainty in climate, as the UGR basin management is not improving resilience sufficiently.

Following a comparative analysis of the two case studies, we conclude with seven interconnected key elements of integrated basin management: comprehensive knowledge, institutional capacity, stakeholder engagement, resilience, transparency, community capacity building, and accountability, which need to be reflected in IRBM despite of different regimes. By considering the past performance of the river system, sustainability assessment proves to be useful for policy-makers and river managers to gain a holistic view of the river basin, to make better-informed decisions with long-term perspective, for management the river with integrated, sustainable manner.

6.2 Recommendations and Future Work

Concept and the methodology

Extend the river sustainability assessment framework to other large river basins, which offers interesting comparisons and insights into different management regimes. For instance, comparisons between silt-laden rivers like the Yellow River and the Colorado, or trans-boundary river basins like the Mekong and the Nile.

Develop a complete set of river sustainability indicators and measurements. This can be done through comprehensive review of other major rivers in the world, different river management regimes, emerging challenges and good practices. This will requires extensive participation of river managers, stakeholders, and communities.

Through such comparative studies, develop a standard/absolute, rather than relative scale to evaluate river sustainability. This allows quantitative comparison across different river basins, could be particularly useful in terms of expediting decision-making process and optimizing plans regarding IRBM.

Besides, future work can also explore evaluating river sustainability through a new angel. For instance, by incorporating the energy, water and food nexus, river sustainability indicators can be applied to measure the correlations or trade-offers between the water, energy and food sectors. Also, the framework can be applied to identify new dimensions of river sustainability, which are barely taken into account in conventional river basin management. This may include aesthetic value and intangible culture value of a river basin.

Application of the assessment framework

Sustainability assessment requires a large amount of data. Data gaps and scarcity in certain types of data are usually identified at an early stage of the assessment. Use of surrogate metrics and estimates can help deal with data shortage, and statistical tools may also be employed. The assessment should not exclude an indicator for the reason of data scarcity. On the contrary, data scarcity addresses the gap in our present understanding and needs for further research. Suggestions could be made to improve monitoring and data collection in this area.

As a multidisciplinary subject, sustainability covers a wide range of topics. To improve accuracy in the estimation of individual indicators, the following two approaches are recommended: first, to obtain high quality data covering a reasonable temporal scale, and second, to encourage stakeholder participation and collaboration with other researchers and professionals.

It would be interesting to examine sustainability of the entire river basin by using the assessment framework, i.e. the Yellow River. This can be done by dividing the river into different sections, with tailored indicator sets determined for different reaches of the river. By carrying out inter-comparisons with regard to the river sustainability performance, this approach can help identify trade-offs between different regions and better inform macro/integrated planning of the entire basin.

The framework can be further used to investigate sustainability trends under different scenarios. Through incorporating climate, flood and drought model, or economic models, the framework can show how the overall sustainability performance of the river response to different impact factors i.e. climate change (with increasing uncertainty of precipitation), population growth (with increase demand for water), economic instruments (such as water allocation permits).

Using the assessment results for policy-making

Application of weightings to different indicators can be particularly useful for underpinning IRBM policies. Water managers who undertake multi-criteria decision-making can run different scenarios to estimate the influence of an individual indicator on the overall sustainability performance of the river. Such an effort could contribute to the prioritisation and/or optimisation of plans.

Construction of a composite index could perhaps provide information for a specific concern. For instance, integrating environmental performance indicators into an index can show ecological river health over time, whilst combining flood risk, drought risk and public health indicators could reveal the trend of vulnerability to water-related risks.

Last but not least, the framework can also help examine impacts of policies on the overall sustainability performance, including land use (wetland restoration), infrastructure development (reservoir, dyke), water allocation regulation (demand management), and IRBM with regard to energy, food and water nexus.

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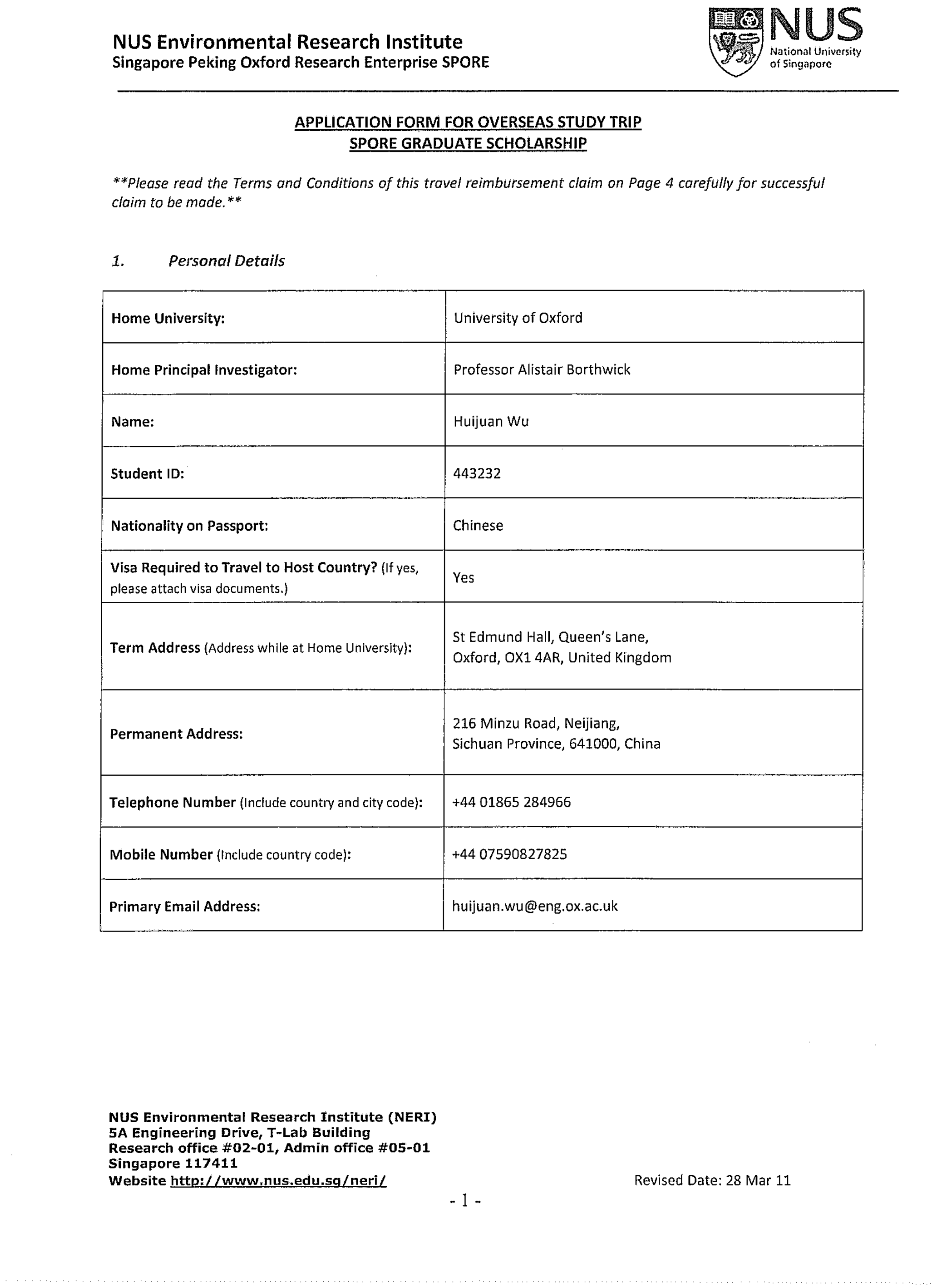
APPENDIX I Research Trip Planning

I.1 Research Trip to China in 2011

I.1.1 Itinerary

Dates	Destination	Activities
30 May 2011 -18 June 2011	Beijing, China	Visiting the Institute of Environmental Engineering, Peking University
19 June 2011 -26 June 2011	Zhengzhou, China	Visiting the Yellow River Institute of Hydraulic Research and Yellow River Conservative Commission
27 June 2011 -8 July 2011	Singapore	Visiting the National University of Singapore Environment Research Institute. Attending Singapore International Water Week

I.1.2 Research Trip Proposal



NUS Environmental Research Institute
Singapore Peking Oxford Research Enterprise SPORE

APPLICATION FORM FOR OVERSEAS STUDY TRIP
SPORE GRADUATE SCHOLARSHIP

Please read the Terms and Conditions of this travel reimbursement claim on Page 4 carefully for successful claim to be made.

1. Personal Details

Home University:	University of Oxford
Home Principal Investigator:	Professor Alistair Borthwick
Name:	Huijuan Wu
Student ID:	443232
Nationality on Passport:	Chinese
Visa Required to Travel to Host Country? (If yes, please attach visa documents.)	Yes
Term Address (Address while at Home University):	St Edmund Hall, Queen's Lane, Oxford, OX1 4AR, United Kingdom
Permanent Address:	216 Minzu Road, Neijiang, Sichuan Province, 641000, China
Telephone Number (Include country and city code):	+44 01865 284966
Mobile Number (Include country code):	+44 07590827825
Primary Email Address:	huijuan.wu@eng.ox.ac.uk

NUS Environmental Research Institute (NERI)
5A Engineering Drive, T-Lab Building
Research office #02-01, Admin office #05-01
Singapore 117411
Website http://www.nus.edu.sg/neri/

Revised Date: 28 Mar 11

2. *Emergency Contact*

Name:	Chengyuan Wu	**Relationship to you:**	Father
Telephone Number: (Include country and city code)	+86 0832 2037137	**Mobile Number:** (Include country code)	+86 13990539917
Contact Address:	216 Minzu Road, Neijiang, Sichuan Province, 641000, China		
Email Address:	Zhongli537@yahoo.com.cn		

3. Academic Details

Degree Program & Major:	DPhil in Engineering Science
Current Year of Study:	1st year
Current CAP (or equivalent):	N/A

4. Purpose of Study Trip

Please write a brief aim and statement of purpose for this study trip (Maximum 500 words).

Your statement of purpose should include what you target to achieve on this study trip and how is it related to your current work or study. Include the name and email contact of the Principal Investigator at the host university.

I'm a first year DPhil student and a SPORE scholar at the University of Oxford. I'm planning a study trip over a six-week period, from 23 May to 9 July, to promote my research on the composite sustainability indices for the Yellow River.

The research aims to derive and evaluate a set of sustainability indices in order to assess the health of the Yellow River, with the view of developing future strategies for river ecological rehabilitation. Through a comprehensive review of literature, I applied the concept of sustainability to river systems and selected the process analysis method to assess river sustainability. A set of sustainability indicators for the Yellow River has also been developed. Next phase of the research will focus on verifications and modifications of the indicators, and developing calculation methods for the indicators.

The purpose of the study trip three-fold.

- First, to visit SPORE professors and scholars at PKU and NUS. This allows me to discuss the project scope with resident Principal Investigators, Prof Jinren Ni (nijinren@iee.pku.edu.cn) at PKU and Prof Fong Yao Li (chmlifys@nus.edu.sg) at NUS, and Dr Tianhong Li (litianhong@iee.pku.edu.cn) a senior researcher at PKU working on the Yellow River.
- Second, to visit the YRCC. The trip to YRCC will be assisted by PKU, aiming to connect with researchers at YRCC, and to collect hydrologic and social-economic data required for calculating the selected

sustainability indicators.

- Third, to attend the Singapore International Water Week and to present my first paper through SPORE. This conference will be very useful, in terms of sharing knowledge and experiences, meeting international researchers on water resources, and exploring the potential for collaboration on the research.

5. Proposed Study Trip Itinerary and Budget

Please list the itinerary and state the expected budget for this study trip.

Eg. Day 1: Discussion with resident Principal Investigator on the project scope.
Day 2 – 3: Field trip to collect samples from reservoirs and river banks.

Itinerary

Week 1-3 (23 May – 12 June) at PKU

- Week 1: Meet with resident Principal Investigator and researchers at PKU. Discuss the project scope, the concept of river sustainability, research methodology, and selected indicators.
- Week 2, day 1-3: Conduct semi-structured interviews with researchers at PKU, with regard to calculations for the indicators and data availability.
- Week 2, day 4-5: Discuss PKU's projects concerning the Yellow River, and explore the potential for further collaboration on the research.
- Week 3, day 1-2: Undertake an analysis of interview notes, modify indicators and calculations.
- Week 3, day 3-5: Arrange a visit to the YRCC and undertake a field trip to the Yellow River.

Week 4 (13 June – 19 June) Zhengzhou

- Day 1: Meet with researchers at YRCC. Discuss the project scope and progress to date.
- Day 2-3: Conduct semi-structured interviews with researchers at YRCC, with regard to the health of Yellow River, river basin management strategies, and related data
- Day 4-5: Collect data and undertake an analysis of the interview notes

Week 5-6 (26 June – 9 June) Singapore

- Week 1, day 1-3: Discuss with resident Principal Investigator and researchers at NUS the project scope and progress to date.
- Week 1, day 4-5: Meet with relevant graduate students and SPORE scholars, share knowledge and experiences.

- Week 2: Attend SIWW and present a paper on 'Pricing Water for Sustainable Cost Recovery: a Study on China's Water Tariff Reform'

Budget

Category	Item	Detail	Amount
Air fare	Economic return from London to Beijing	Fly with Lufthansa Depart on 22 May, return on 10 July	£ 370 (approx. S$ 760)
Air fare	Economic return from Beijing to Singapore	Fly with AirChina Depart on 26 June, return on 9 July	£ 320 (approx. S$ 650)
Conference fee	Singapore International Water Week registration	Discounted rate for oral presenters	S$ 960
Per diem expense	Accommodation and subsistence in Singapore	Per diem expense S$ 150 X 12 days	S$ 1800
		TOTAL **TOTAL CLAIMABLE**	S$ 4170 **S$ 4000**

6. Approving Authority

	Name	Signature	Date
Home Principal Investigator:	Professor Alistair Borthwick	Alistair Borthwick	3/5/2011
SPORE Program Director:			

I.2 Research Trip to China in 2012

I.2.1 Itinerary

Dates	Destination	Activities
29 August 2012 21 September 2012	Beijing, China	Visiting the Institute of Environmental Engineering, Peking University
22 September 2012 28 September 2012	Zhengzhou, China	Attending the 5th International Yellow River Forum Visiting YRCC and YRIHR

I.2.2 Email correspondents regarding trip arrangements

发件人: Huijuan Wu [mailto:huijuan.wu@eng.ox.ac.uk]
发送时间: 2011 年 5 月 13 日 6:34
收件人: liang linlin
主题: RE: Enquiry SPORE study trip arrangement

Dear linlin,

Thank you for the email and I'm really glad to hear from you.

As Prof Ni will be away in late May, I'm thinking to visit my family first after arriving in China, I'll then come to visit PKU from 29th May to 18th June. I would very much appreciate if you can find a room for me during the time. I fully understand the difficulty so I don't mind changing room/place during the stay, and any type of accommodation will do. Also, I should be able to settle myself on the 端午 weekend (4th and 5th of June), if there is no vacant rooms.

Besides, do you need my passport number for room booking , and ID photo for a visitor's permit card? If you need any further info please don't hesitate to contact me.

Thank you very much in deed and I'm looking forward to seeing you.

With best wishes,
Huijuan

From: liang linlin [mailto:lianglinlin@iee.pku.edu.cn]
Sent: 12 May 2011 02:14
To: Huijuan Wu
Subject: 答复: Enquiry SPORE study trip arrangement

Dear Wu Huijuan,

I have talk with Prof. NI about your visiting, either period is OK for us. Prof. Ni will be in USA from 22 May to 29 May, I hope it makes no difference.
But now still have a problem, I try to book a hotel or apartment for you, but it's difficult to book such a long-period room in both May and June in PKU.
If you decide your schedule please let me know and I'll try my best to book a suitable room for you.

Looking forward to seeing you in PKU.

Linlin LIANG

发件人: Huijuan Wu [mailto:huijuan.wu@eng.ox.ac.uk]
发送时间: 2011 年 5 月 4 日 22:07
收件人: lianglinlin@iee.pku.edu.cn
抄送: Alistair Borthwick; nijinren@iee.pku.edu.cn
主题: Enquiry SPORE study trip arrangement

Dear Ms Liang,

Greetings from Oxford. I’m a DPhil student and a SPORE scholar working with Prof Borthwick. I’m writing to ask for your kind help in arranging a study trip to PKU.

I’m planning to spend 3 weeks in PKU, followed by a trip to the YRCC. I’ll arrive in Beijing on 20 May, and hope to visit PKU from 23 May to 10 June (or 30 May to 17 June, whichever is more convenient to you). Can you arrange accommodation for me during the time? I’ve attached the application form for SPORE travel grant (including the itinerary) for your information. Please don’t hesitate to contact me if you have any inquiries. Your help would be highly appreciated.

Thank you very much and I look forward to hearing from you soon.

Thanks and best regards,
Huijuan Wu
DPhil candidate reading for Engineering Science
Singapore, Peking and Oxford Research Enterprise Scholar
University of Oxford

I.3 Research Trip in 2013

I.3.1 Itinerary

Dates	Destination	Activities
12 July 2013 - 19 July 2013	Chengdu, China	Pre-trip preparation
22 July 2013 - 14 September 2013	New Delhi, India	Visiting Council on Energy, Environment and Water
24 August 2013 - 27 August 2013	Rishikashi – Haridwa - Dehradun, Uttarkhand State, India	Road trip to the research site, upper reaches of the Ganges; Visiting the People Science Institute

I.3.2 Email correspondence regarding research site visit

---------- Forwarded message ----------
From: **Huijuan Wu** <huijuan.wu@eng.ox.ac.uk>
Date: 23 August 2013 at 18:28
Subject: Dehradun visit
To: Nirmalya Choudhury <nirmalya.choudhury@ceew.in>, Swati Trehan <swati.trehan@ceew.in>
Cc: "whjtracy@gmail.com" <whjtracy@gmail.com>
Dear Nirmalya and Swati,

As you are aware I'll be travelling to Uttarakand tomorrow and visit People Science Institute in Dehradun next week. Please see below my travel itinerary and contact info. I'll keep you updated when I reached there/safely back.

Best wishes,
Huijuan

Travel itinerary
Monday 26 August
Haridwar to Dehardun Train Number: 12055 Departure/arrivial: 19:40 – 21:10
Tuesday 27 August
Dehradun to New Delhi Train Number: 12018 Departure/arrivial: 17:00 – 22:45

Local Contact
Dr. Ravi Chopra
People's Science Institute 653, Indira Nagar Dehra Doon - 248 006 Uttarakhand
Email:psiddoon@gmail.com
Mobile: +91 9411 135 976
Tel : 0135 - 2763649 Fax : 0135 - 2763368

Emergency Contact:
Sukarni Wheeler
Department of EngineeringScience, University of Oxford
Email: sukarni.wheeler@eng.ox.ac.uk
Tele: +44 01865 273011

I.3.3 Research Trip Risk Assessment Form for Research Trip to India

Department of Engineering Science: Risk Assessment
Risk Assessment: Travel from Oxford to Chengdu in China, and New Delhi in India for 3 months. **Exact Location for stay:** 216 Minzu Road,Neijiang, Sichuan,China (12 Jul – 19 Jul, 19 Sep – 6 Oct 2013); Council on Energy, Environment Water, Thapar House, Janpath, New Delhi 110001, India (22 Jul – 14 Sep) **Dates of Travel** : Outward 11 Jul 2013 homeward 7 Oct 2013 **Those Travelling**: Huijuan Wu
Risk Assessment completed by: Huijuan Wu
Date of Risk Assessment: 2 July 2013

Trip in India

Hazard	**Person(s) at Risk**	**Risk Controls on Place**	**Risk Rating (Severity x Likelihood)**	**Further Action to Control Risk**
Travel from Chengdu to Airport:	Myself	Travel by taxi	Low	Fasten seat belt. Obey driver's instructions.
Accident on route.			Low	
Flight from Chengdu to New Delhi, stopover in Singapore.	Myself	Travel with Air China and Jet airlines on scheduled flight.	Low	The airline will cancel the flight if weather conditions are not appropriate or in the presence of volcanic ashes or in case of technical or other fault.
Accident on route.		Aeroplane travel is recognised as a very safe form of travel. All responsibilities for safety lie with the aeroplane company. By pre-arranged taxi from hotel.	Low	

Transport from Airport in New Delhi to location of stay. Accident on route.	Myself.		Low	Fasten seat belt. Obey driver’s instructions.
Travel locally in New Delhi and surrounding areas Abduction. Mugging.	Myself with either colleagues or friends.	By car, taxi, metro or other public transport. Dress Down and do not carry expensive items e.g. camera’s which highlight traveller status.	Low/Medium Medium	Fasten seat belt. Obey driver’s instructions. Read Advice before travelling from the FCO office on safe ways of travelling in India.
Travel around at night. Abduction. Mugging. Harassment.	Myself with either colleagues or friends.	Avoid any unnecessary travels after dark. Always travel with colleagues or friends, and never walk home alone. When travelling around New Delhi, check on the location you are travelling to and from. Take a good map of the local area. Have a contact number and mobile telephone for making contact is required. Have emergency contact number in phone, and stay alert all the time.	Medium/High	Stick to well-frequented central parts of city. Gather advice from those living in the immediate area concerning local issues/hazards.
Illness whilst travelling away e.g. Food poisoning, general ill health etc	Myself with either colleagues or friends.	Get vaccinations in advance. Prepare travel medicines and first aid kit. Ensure appropriate medical cover whilst travelling. Carry documents. Have access to	Medium/High	Seek Local advice. Avoid tap water, street food, and any strange foods or drinks.

Others: academic visits in New Delhi India. Accident on route. Abduction. Mugging. Harassment.	Myself with either colleagues or friends.	mobile phone and point of contact. Take medication if required. By taxi or public transport. Travel where possible with a colleague; Take a good map of the local area. Have a contact number and mobile telephone for making contact is required.	Low/Medium	Avoid raw food, never eating or drinking in unhygienic settings. Stick to well-frequented central parts of city. Stick to well-planned trip. Get in touch with people to visiting in advance. Gather advice from those living in the immediate area concerning local issues/hazards.

APPENDIX II Stakeholder Interviews

II.1 Sample of Stakeholder Interview, 2011 China

Interview Information
Interview Date: 30 May 2011
Interview Type: face-to-face interview
Interviewee Name: Jinren Ni
Position: Professor in Environmental Engineering
Institute: Institute of Environmental Engineering, Peking University
Contact: nijinren@iee.pku.edu.cn
Expertise: River sustainability; Water and sediment science; Water treatment;
Profile: http://en.cese.pku.edu.cn/index.php?action=viewteacher&id=41

Summary of Interview:
Question (Q):
Dear Prof Ni, I'm a DPhil candidate in water resources management at the University of Oxford. I'm working on integrated assessment for large river basins by using sustainability indicators. This research project aims to define river sustainability, develop and validate a methodology for measuring river sustainability. I'm applying this methodology to the Yellow River, to examine the underlying sustainability of the river basin, to understand its performance towards sustainable development, and to provide evidenced-based policy recommendations for integrated river basin management.

To carry out the case study, insights from stakeholders are very important. Your contributions are highly valuable in delivering the research. We've prepared a list of semi-structured questions for this interview. I hope you can provide your candid opinions to all the questions. Thank you very much in advance.

Could you first introduce your research interests and your work on the Yellow River please?

Answer (A):
Thanks Huijuan. I'm happy to contribute to your research. I'll answer the questions to the best of my knowledge.

My research interests include water and sediment science, wastewater treatment and river health assessment. I've been working on the Yellow River for the past 20 years, mainly focusing on sediment transport mechanisms, hydrological modelling, flooding and drought risk analysis, and river health assessment in recent years.

Q: What are the characteristics of the Yellow River? What distinguishes the Yellow River from other rivers?

A: Every river course is different from others. Yellow River is named after its high sediment load. This is the distinguishing characteristics of the Yellow River. Yet, high sediment load presents enormous challenges in managing the river course: river channel in the lower reaches silt-up due to sedimentation, relocation of river course occurred many time in recorded history, which resulted in extreme floods with devastating consequences.

As you know, the Yellow River is also called mother river of China, it's the cradle of Chinese civilization. Yellow River basin is highly populated comparing to other large river basin in the world, i.e. Amazon or Mississippi. Therefore, interactions between human society and the river ecosystem must be carefully studied, and a balance must be maintained.

Q: What are the challenges to management the Yellow River? And what are the most pressing issues?

A: In China, how to manage the Yellow River has been under debate for thousands of years. The challenges, in brief, are to alleviate flood and drought risks, to utilize the limited water resources for human use, to transport sediment in an efficient way, and to prevent the water quality and river ecosystem from degradation.

In the context of climate change and fast growing economy, the emerging challenges for managing the Yellow River include, increasing uncertainties in annual renewable water resources due to climate change, increasing demand needs for water, degrading water quality, and competing needs for water from different provinces and different sectors.

Q: Facing all the challenges, could you explain the current management strategies for the Yellow River Basin?

A: YRCC is the government agency in charge of integrated management of the Yellow River. YRC proposed the new concept (management strategies) in 2002, namely, maintaining healthy life of the Yellow River. In practice, a four nots principles services as the guideline for managing the river. There are, the dike does not breach, the channel does not have zero-flow, the pollution does not exceed the standard, and the riverbed does not rise up. Nine approaches have been adopted in order to achieve healthy life of the river, including,

- To reduce the sediment load
- To manage the water resources utilization more effectively
- To increase the water resources through diverting water from other river basins
- To build the water and sediment regulating system
- To work out and execute a scientific and rational general plan for regulating the downstream channel
- To create a runoff process that does not cause shrinkage of the main channel
- To adopt water resources protection measures that meet the requirement of water quality functions
- To harness the estuary of the Yellow River so as to maximally reduce the impacts on the river channel
- To create a runoff process that meets the requirement of maintaining the benign cycle of the ecological system in the delta region

Q: Based on river health assessment for the Yellow River you've conducted, could you please explain what does healthy river means?

A: Healthy River in short means river in ecologically good condition. This is a word borrowed from, i.e., the healthy status of a person, it is grounded in science yet speaks to communities. It conveys the concept of maintaining and restoring the natural structure and function of ecosystems of a river and its catchment.

Q: How do you measure river health of the Yellow River? What's the process of selection indicators?

A: We use indicators to measure different river functions, then combine these indicators into a River Health Index by applying weights to different indicators. The selection of indicators are based on reviewing nine major functions of a river system, namely, flood discharge, sediment transport, ecosystem support, self-purification, water abstraction, hydropower generation, navigation, and recreation. And these nine functions presents the final nine indicators used to construct the River Health Index.

Q: How do you think river sustainability differentiates from river health?

A: To my understanding, the terms of river health and river sustainability are interconnected, but different. River health has a focus on ecological condition of the river, whether all the major river functions have been properly maintained. The concept of river health treats the river basin as a whole, and helps provide an overall picture of the holistic status of the river, which is particularly useful for underpinning integrated river basin management.

River sustainability should take into account the needs for development, whether the river ecosystem can function well, at the same time support socio-economic development. Therefore, river sustainability assessment must consider all three domains of sustainability at the same time, the environment, the society and the economy.

Q: Based on our working definition of river sustainability, the first perspective is resources sufficiency. Could you please explain the status of resources efficiency in the Yellow River basin?

A: Yellow River basin faces severe shortage of water, mainly due to decreasing annual renewable water resources, degradation of water quality and increasing demands. It also became more difficult to utilize water resources due to increasing uncertainty in precipitation and flow patterns.

Lower Yellow Basin experienced extreme droughts in the late 1990s. In Lijin station, over 220 days in 1997 there was no flow in the mainstream. This devastated the river ecosystem, and caused extreme water tension for the people who depend on water supply from the Lower Yellow River.

To tackle the water scarcity problem, a few actions were taken. Most importantly, multi-functional infrastructures were built to regulate water resources. Xiaolangdi Reserovoir which regulates water resources in the Lower Yellow River was built in 2002. A minimum environmental flow in the Lower Yellow River has been secured and the no-flow event did not occur again since then. Besides, implementation of water allocation policies, water demand management, water conservation campaigns also contribute to reduce water stress.

Q: Except water shortage, what are the water security concerns in the Yellow River Basin? How are the communities adapting to these?

A: Although renewable water resources decline, increasing uncertainty in climate poses very high risks of flooding in the Yellow River basin. This is also due to sedimentation process when the flow rate was low. As the river channel silts up, the river channel losses its capacity to discharge floods. New dykes have been built (in 2007) all along the lower Yellow River to alleviate flood risks.

Another big concern is water quality degradation, which brings long-term public health issues. Whilst the occurrence of water contamination incidents have immediate impacts on social-welling and local economy. To adapt to this, water quality monitoring has been enhanced by YRCC over the past 10 years, which provides quarterly water quality reports to the public. In some cities, early warning system has also been establish to inform local communities in the case of water contamination.

Q: Water supply and sanitation are the basic needs for human beings. Can you explain the status of water utilities development in the Yellow River basin?

A: In general, water utilities are developing rapidly in China national wide since 1979, the Open Doors Policy. Water is considered as public goods, therefore water unities are greatly subsidized by the government. Since 1990s, private sectors are allowed in the investing in water utilities. Now, most urban areas in the Yellow River basin have public water supply and sewage system. For peri-urban an rural areas, you may need to contact local government for the status of water utilities development.

Q: Referring to equity issue in water resources management, are there any good practices in the Yellow River basin?

A: As far as I know, Yellow River basin has the first water permits trading platform in China, which complements the Yellow River Water Allocation Policy issued in 1987. This helps balance the competing needs for water resources between upstream and downstream provinces, and among different sectors in one province.

Q: Thank you very much Prof Ni. This is all the questions for the interview today. May I contact you in the near future for your comments on the selected sustainability indicators for the Yellow River?

A: You’re welcome. Yes you may send me your work. Keep in touch.

II.2 Sample of Stakeholder’s Interview, 2011 China

Interview Information

Interview Date: 30 May 2011
Interview Format: email correspondence
Interviewee Name: Mr Simon Spooner
Position: Priniciple scientist at Atkins Global
Manager of the EU-China River Basin Management Programme
Company: Atkins Global
Contact: Simon.Spooner@atkinsglobal.com
Expertise: Water resources engineering and management, river basin management, water quality monitoring
Profile: https://www.linkedin.com/in/simon-spooner-a3502311

-----Original Message-----
From: Huijuan Wu [mailto:huijuan.wu@eng.ox.ac.uk]
Sent: 07 October 2011 00:09
To: Spooner, Simon
Subject: RE: EU-China River basin management programme

Dear Simon,

Greetings from Oxford. My name is Huijuan Wu. I'm a DPhil student working with Alistair and Richard (also Prof Jinren Ni in PKU) on river sustainability assessment for the Yellow River. (I did my undergraduate studies in China, the a MSc in water science, policy and management at Oxford. Besides I worked for Halcrow for about 2 years).

Alistair has told me about your project on river basin management, which is really interesting and relevant to my research. Apologize for not contacting you earlier. I have been waiting for some progress/outcome. Please see attached an abstract of my research, recently submitted to an IWA conference. I would appreciate your comments on it. (More details are available in my transfer report, I could send you a copy later on if you are interested.)

Your project on pollution load management sounds very interesting. Could you kindly share with me any publication and reference? I visited the Yellow River Institute of Hydraulic Research this summer, and learned about the river health assessment project (with Australian universities). Is the handbook associated with the ecological and biological survey in 2008, and will this serve as guideline for future work? I would appreciate if you could keep me updated on the progress.

Please take care and keep in touch. Wish you all the best in China. And I look forward to seeing you in Zhengzhou I the future.

With best regards,
Huijuan

-----Original Message-----
From: Spooner, Simon [mailto:Simon.Spooner@atkinsglobal.com]
Sent: 28 October 2011 14:10
To: Huijuan Wu
Cc: Alistair Borthwick; nijinren@iee.pku.edu.cn

Subject: RE: EU-China River basin management programme

Dear Huijian,

Sorry to be a bit slow reply.

The CRSI index is a good idea. But it is always very difficult to decide on what the parameters to include should be. Hence under WFD in EU the vague "good ecological status" target then years of wrangling about what it means. In China the River health assessment is the system currently under development by MWR to be a formal assessment system. This will incorporate statutory / policy targets such as 3 red lines that then link to administrative official's personal performance assessments (and so promotion / remuneration opportunity). This aspect of strategy is set out in the No 1 policy document on accelerating investment in water (attached copy in English, can send Chinese). I assume that you have seen the MWR guidelines on river health assessment which are currently being piloted and under review, if not can send. The Australian ACEDP project has fed into this process a bit, though mostly operated independently of the primary policy and guideline development process of MWR. Below are links to their latest reports, which are really very good if you have not seen before.

Our programme (EU-China RBMP) has also produced documents relating to ecological assessment, attached is the draft of a handbook on how ecological assessment has been implemented in Europe to act as a reference for those implementing it in China. To this will be added a comparison to Chinese practice to be prepared by YRCC WRPB The MWR initial draft guidelines drew heavily from the earlier training and publications of the programme in WFD and biological monitoring, and also from US and Australian experience.

Regarding the pollution load management work, I attach the terms of reference for our research study which sets out the issues and can send reports a bit later when they are ready. This includes setting out the procedure for using a model for the calculation of river basin pollution indices which can be very useful in planning optimised strategy for working to achieve water functional use zone targets. The model software has been developed by myself over many years, and applied in UK and China in many catchments, and provides a framework for such calculations, now adapted to the specific requirements of the Chinese Carrying Capacity and pollution load management approach for achieving (or not) the Water use functional zone targets set by each province and endorsed by the state council.

To my opinion me the really big goal would be to formulate a definition of river quality and status that embraces the fact that for modern society the ideal outcome is not to return the river to some mythical unspoiled reference condition but to farm the river such that it sustains the most healthy ecosystem that can purify itself and sustain the human society dependent on it in the most healthy manner over the long term. This means well managed, not polluted beyond its capacity to self purify and the morphology and flow regime managed to sustain healthy and diverse ecosystem - Basically maximise eco system services delivery. In addition to the management of flood, drought, sediment, pollution risks etc.

But this is still a concept difficult to express and quantify. The CRSI you present appears to cover most of the points related to this, and the concepts of risk based approaches, but it is hard to get this simplified to be an effective administrative tool. There is so much to decide about how each factor is weighted, measured and assessed.

I also attach the general brochure on our project, more info available from our website. In my parts of the programme I look at various aspects from the institutional issues in China that limit cooperation between sectors (especially the MWR / MEP splits), the manner to calculated Carrying capacity and pollution load management, how to deal with acute pollution incidents following accidents, the means of promoting clean technologies for pollution reduction at source and for water saving, and the mechanisms for moving towards an ecological assessment of the Rivers and lakes. Elsewhere in the programme we address issues of climate change adaptation and how to implement IRBM. I also manage studies on how the concepts of decentralised waster water treatment and reuse can aid water saving and pollution reduction. Our final major deliverable will be on how these concepts are to be implemented over the next 10 years through China's policy for water resources as expressed in the No 1 policy document. This is to be presented by the Water minister at the world water forum in Marseilles in March next year. The legacy is to be the China Europe water platform to establish mechanisms and institutions for future dialogue between Europe and China on water related issues, on a partnership rather than aid basis.

I hope that this information is of assistance to your studies, sorry if a bit disorganised I write in airport waiting for an aeroplane.

I hope someday to get opportunity to meet Dr Ni and build on existing relations with Peking University.

Best regards

Simon

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The Liao and Pearl pilots studies used a significantly different method from that in the Yellow River. They tested indicators against a disturbance gradient, calculated based on land use upstream of sampling sites. The approach wasn't suited to the Yellow River pilot, which as you will know only looked at the lower reaches. Chris suggested that the Liao/Pearl approach might be of interest to you in relation to your work in the upper reaches of the Yellow.

The Liao and Pearl reports, as well as summary report cards, are already on the IWC website:
http://www.watercentre.org/projects/acedp

You can download copies of the other reports here:
http://www.box.net/shared/static/ouoztsbuuobrdtb9lyzv.pdf
http://www.box.net/shared/static/djosk8t3bjdpt4fgspv7.pdf
http://www.box.net/shared/static/biloy6nxaijfsjap73fz.pdf
http://www.box.net/shared/static/d9b1itn2f5jfrlyvtgr0.pdf
http://www.box.net/shared/static/e5yj2kcv0l21nzr4bbkg.pdf

-----Original Message-----
From: Huijuan Wu [mailto:huijuan.wu@eng.ox.ac.uk]
Sent: 24 December 2011 18:52
To: Spooner, Simon
Subject: Merry Christmas and Happy New Year

Dear Simon,

Greetings from Oxford. Hope you've been keeping well.

Really sorry for not being in touch for a while. I recently attended the UN climate change conference COP17 in Durban of South Africa, as a member of the China Youth Delegation. Observing climate change negotiations is a great experience. Although the outcome has been criticized as not ambitious enough, the positive part is a new legal binding covering both developed and developing countries (yes,including US, China and India), will be placed by 2015 then come into force in 2020. Besides, I'm interested in discussions on water and climate change. This was highlighted in the Nairobi work programme; further info please see: http://unfccc.int/resource/docs/publications/11_nwp_clim_freshwater_en.pdf. IPCC also released a new report on extreme events.

Thank you very much for the documents, very useful indeed. I've spent some time reading through (and will spend more). According to your email, I'm thinking to attend the 6th world water forum in Marseille next March. Also I've put a paper/abstract for the 5th Yellow River International Forum, next Oct in Zhengzhou.

Have a great Christmas break. Wishing you and your family a Merry Christmas and a prosperous New Year of 2012.

Take good care and I look forward to seeing you in the near future.

With best wishes,
Huijuan

-----Original Message-----
From: Spooner, Simon
Sent: 25 December 2011 21:49
To: 'Huijuan Wu'
Subject: RE: Merry Christmas and Happy New Year

Dear Huijuan

Merry Christmas

Our work on the development of the Biological monitoring criteria in China has progressed very well and we are now working directly with the technical working group developing the guidelines for China. As part of that process we produced a Guidance document on how such monitoring is done in Europe, as mentioned before.

Attached is a copy of that document, in English and in Chinese, this will shortly be produced as a book for publication.

I will look again at your work on CRSI and see how that relates. We have just finished training courses on this EU approach to monitoring in the Yellow and The Yangtze River basins, which included comparisons to the methods that they have piloted in various river basins.

I look forward to see you in Marseilles and again in Zhengzhou at IYRF.

Best regards
Simon

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Simon.Spooner@atkinsglobal.com

-----Original Message-----
From: Spooner, Simon [mailto:Simon.Spooner@atkinsglobal.com]
Sent: 11 January 2012 01:45
To: Huijuan Wu; nijinren@iee.pku.edu.cn
Subject: EU-China River basin management programme: River health Assessment, CRSI indexing
Importance: High

Dear Huijian and Prof Ni

Our project team will be meeting this Friday to discuss ecological monitoring and river health assessment with the Technical group at IWHR and their political leaders from MWR responsible for the revision and finalisation of the MWR guidelines on monitoring and river health assessment. In the training courses and debates last year a major point of controversy was whether it is valid to use composite indexes for river health assessment or whether they are infact misleading.

Please could you send me the full paper on CRSI and other relevant short papers related to this, I can then review before the meeting and any formal submission of recommendations to MWR on this point. The abstract was very interesting.

I write this also to Prof Ni Jinren in hope that you may also help with advice on this matter. This is a rare opportunity for the research to impact on the policy process. I can send to you directly the latest versions of our handbook on EU methods of Ecological monitoring prepared for MWR. Hopefully soon we can find a time to meet in Beijing

Best regards

Simon

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Simon.Spooner@atkinsglobal.com

-----Original Message-----
From: Huijuan Wu
Sent: Thursday, 12 January, 2012 8:01 AM
To: Spooner, Simon <Simon.Spooner@atkinsglobal.com>; nijinren@iee.pku.edu.cn
Cc: Alistair Borthwick (alistair.borthwick@eng.ox.ac.uk) <alistair.borthwick@eng.ox.ac.uk>; Richard Darton (richard.darton@eng.ox.ac.uk) <richard.darton@eng.ox.ac.uk>
Subject: RE: EU-China River basin management programme: River health Assessment, CRSI indexing

Dear Simon,

Thank you very much for the email. The meeting sounds very important and interesting. I found it's a great opportunity for engineers and consultants having their say, further influence decision of policy makers.

Please see attached a copy of my transfer report. It reviewed the literatures and methodologies for CRSI, also set directions of the research through the case study of the Yellow River. You may also be interested in the paper on 'Rapid assessment of sustainability in Mainland China' (Sun, Ni and Borthwick, 2010), using a multilayer index system (very similar to CRSI). It's quite a comprehensive study on sustainability assessment at the national scale. I feel this could be a good example of CSI in practice.

As for the IWA WCE conference, our abstract has been selected for presentation, while we are still working on the full paper. I'll let you have a copy as soon as it's available.

Besides, there is a very relevant thesis on 'Sustainability Metrics for the Yellow River', by a previous research student in our group. It might be a bit too long for the meeting (over 150 pages as I remember). Please let me know if you think it's useful, and I'll send you a copy after consulting my supervisor.

With best regards,
Huijuan

II.3 Sample of Stakeholder's Interview, 2013 India

Interview Date: 27/08/2013
Interviewee Name: Dr. Ravi Chopra
Institute and Position: People's Science Institute, the founder and director
Contact: psiddoon@gmail.com
Expertise: water resources management, environmental quality monitoring and disaster mitigation
Profile: http://peoplesscienceinstitute.org/aboutUs/Staff%20List/Ravi.html

Summary of Interview
Question (Q):
Dear Dr. Chopra, thank you very much for having me here at the People Science Institute (PSI). To start with, I'll briefly introduce my research and the purpose of this interview.

I'm currently a doctoral student at the University of Oxford, and my research topic is water resources management. I'm working on integrated assessment of large river basins by using sustainability indicators. This research project aims to define river sustainability, develop and validate a framework for measuring river sustainability. I would like to apply this framework to the Upper Ganges basin, to examine its underlying sustainability in terms of environmental performance, social wellbeing and economic development.

To carry out the case study, insights from stakeholders are gained from semi-structured interviews. Your contributions are highly valuable for delivering the research. We've prepared a list of questions for this interview. I hope you can provide your candid opinions, and thank you very much in advance.

First, could you introduce PSI and your work on the Ganges please?

Answer (A):
Welcome to visit PSI Huijuan. I'm happy to help with your research.

PSI is founded by a group of professional engineers and environmental scientists in 1988. It is a non-profit research organization based in Dehradun, the main city of the Upper Ganges river basin. PSI aims to put science and technology in the service of India's poor. We focus on building the capacities of the poor to plan their own development, implement projects and then manage the assets created. We provide technical and managerial support to communities; implement development programmes and undertakes public interest research. Our fields of work include community-led watershed-based livelihoods development, environmental quality monitoring, disaster-safe housing and dissemination of appropriate technologies.

As a researcher, I have worked for nearly four decades in the Upper Ganges on the interactions between technology and society and, environment and development. My fields of work include using science and technology for empowering the poor, protecting ecosystem of the Upper Ganges, rehabilitating survivors from natural disasters, enhancing access to safe drinking water and decent sanitation, and promoting efficient use of water resources.

Q: What are the characteristics of the Ganges? And what distinguishes the Ganges from other rivers?

A: Ganga is declared as the National River of India. It symbolizes the national heritage and identity of India. In Hinduism, the river Ganga is sacred and represents the goddess Ganga. It is worshipped by Hindus who believes that bathing in the river can remission their sins and purify their spirits. Ganga is also one of the most densely populated and fertile river basins in the world. It provides millions of people water to support their everyday life.

Q: Please explain the socio-cultural value of the Ganges.

A: The socio-cultural value of Ganga is intangible assets to Hindus. As you might have observed during your trip, hundred of thousands of people gather everyday along the Ganga at different locations for worships. This is quite unique, and shows how religious significance of the Ganga.

Yet, it would be very difficult to measure the socio-cultural value. We've done some preliminary surveys during the Kumbh Mela in 2011, one of the largest gatherings of people for a religious purpose, held every 12 years at Upper Ganga, to study the and environmental flow socio-cultural significance. From the study most people interviewed believed that a holy river should be clean and free flowing. For years the spiritual purity of Ganga has remained unchanged, but her physical pristine condition has deteriorated. Many expressed their dissatisfaction with the inadequate level and bad quality of water during the 2011 Kumbh. As you see, socio-cultural aspects of the river are closely linked to environmental health of the river, and possible environmental indicators might be used to measure socio-cultural concerns of the Ganga.

Q: Please summarize the most pressing sustainability concerns about the Ganges?

A: India's booming population and economy has put enormous pressure on the Ganga. The biggest concerns are, water pollution due to excessive abstract and unregulated wastewater discharge. This resulted in serious water quality degradation. Climate change is another big threat. Flooding risk has been ever increasing in the recent 20 years in Upper Ganga. The damage of extreme events is multiplied by poor administration. Early this year (June 2013), a devastating flood killed over 5000 (as estimated) people in this region. It is believed that many man-made factors, including unregulated urban development in floodplain, unchecked small hydropower projects, lack of early warming system and timely rescue, turned this extreme flood event into a catastrophe.

Q: What are the challenges for managing the Ganges?

A: The management of Ganga is fragmented due to decentralization of government in India. Water resources usage and planning are decided by individual state, and has little influence from the central ministry. National Ganga River Basin Authority (NGRBA) was established in 2009 by the central government, under the Ministry of Water Resources. Nevertheless, NGRBA has not got the power nor capacity to make integrated strategies for the river basin.

Q: Could you share your opinions on short-term and long-term goals with regards to managing the Ganges?

A: From a short-term perspective, management of Ganga should focus on water pollution control, flood alleviation and prevention, disaster management and stringent regulation of hydropower infrastructures. In a long run, NGRBA should make integrated planning for the whole river basin, bearing in mind risks and uncertainties, to enhance water security for the poor living in the river basin, and to use water resources in an efficient way to support growing economy.

Q: According to our working definition of river sustainability, the first perspective is concerned with resources sufficiency. Have there been sufficient water resources in Upper Ganges to support the ecosystem, social wellbeing and economic development?
A: Upper Ganga sources water mainly from glacier and precipitation. Generally speaking, there are abundant renewable water resources. However, the level of environment flow has gradually decreased in recent years. This is largely due to unregulated development of small-scaled hydropower plants. Large amount of water resources are stored up for power generation. Because of poor planning and regulation, the downstream flow rate has been affected badly.

Q: Are there other impacts due to these hydropower projects?

A: Yes, they have huge impacts on the local environmental, especially on local forests. They also generates large amount of wastes, which are not properly disposed. The impacts on social security are also significant: these projects reduce average environmental flow, therefore, some local residents, especially the poor, started to move to and settled down in floodplains. In the case of an extreme event, these small-scale dams are incapable to deal with the storm surge, therefore intensify the flood risks by putting the people in risks. This is one major factor causing the tragedy during the flood this June.

Q: In this sense, do you think these hydropower plants should be abandoned?

A: Yes, development of small-scale hydropower plants should be ceased. Well, I’m not entirely anti-hydropower. Hydropower is a valuable source of energy. And indeed, there is increasing demand for energy to support socio-economic development.

However, there must be proper planning and regulation, which makes sure the impacts are minimum. And the hydropower resources must be used in an efficient way. Uttarakhand State planned nearly 700 dams in 2011, out of which only 155 are 5 megawatt or above. PSI has done environmental impact assessment for these projects. Our studies show that they have huge impacts on the fragile local ecosystem. In my opinion, some of these small-scale projects are totally unnecessary. There are many alternatives to avoid these dams or to make them less damaging. Solar energy can be a good alternative to hydropower in this region. Promoting energy conservation is another.

Q: You mentioned the devastating flood this June, could you explain how can we adapt to it better, and how to increase resilience to extreme events like this?

A: The north India flood earlier this year is a heavy lesson. There are many man-made factors, including change of the topography of the religions by deforestation, block the river channel by construction of dams, sand mining in the river course, and infrastructure development for human settlement in the flood plain, and lack of warning system or timely relief-action from the government. These all contributes to the tragedy.
In the context of climate change, we must have comprehensive adaptation strategies to extreme events like this. Most importantly, there must be institutional change for managing the river basin. Integrated planning with long-term perspective is essential. The government should up their capacity for integrated planning, policy implementation and faster, better relief-actions.

Q: Has the water quality in the Ganges improved or degraded, and what are the possible reasons?

A: Water in river Ganga is heavily polluted nowadays, especially in the lower reaches, for example, Varanasi. In the Upper Ganga, water quality is acceptable, but has degraded significantly in the past decade. This is largely due to fast growing population and economy, but lack of wastewater treatment capacity. Agriculture accounts for the majority of non-point source of wastewater discharge, which can hardly be counted. Industries and domestic wastes (point source) are often discharged to the river without any treatment.

Q: Following your comment on lack of wastewater treatment, have the MDGs goals with regards to sustainable access to safe drinking water and basic sanitation been achieved?

A: Yes, access to drinking water and sanitation has been largely improved in the past ten years. Thanks to the efforts of public and private sectors, and international organizations i.e. World Bank and Asian Development Banks. Yet, there is still long way to go before achieving full access, especially for the poor. Also, water quality monitoring is essential, and better sanitation facilities are needed to improve the life quality of many local residents.

Q: That’s all for today. Thank you very much for your time. Do you mind sending me the links of the researches and projects you mentioned? And may I phone you next week with regard to my selection of sustainability indicators for the Upper Ganges? Your comments will be much appreciated.

A: Sure. I’ll send you the info mentioned earlier. Do remind me if I miss anything. And it would be lovely to speak with you soon about your indicator set. Safe trip back to Delhi.

II.4 Invitation letter to Upper Ganga presentation

‘Integrated River Sustainability Assessment: Studies of the Yellow River and Upper Ganga’

with

Ms Huijuan Wu

DPhil in Engineering Science at University of Oxford

Date: 11 September 2013

Time: 15.00 – 16.00 hrs

Venue: CEEW Conference Room, Thapar House, 124, Janpath, New Delhi-110001

Abstract

Integrated management of large river basins has become critical for emerging economies facing the growing scarcity of water, affected by climate change and population trends. The discussion will focus on how an indicator-based framework contributes to integrated assessment of large river basins. Starting with a review of sustainability measures and metrics, we will outline the Process Analysis Method as a holistic approach for engaging stakeholders and generating indicators. The case study of Yellow River will be featured in the presentation. We will identify indicators and indices by investigating the impact generators and incorporating all domains of sustainability. By analysing the tailored indicator set, the assessment provides us with quantitative understanding of the river’s sustainability. We further look into how this methodology can be applied to the Upper Ganga in India, leading to an integrated sustainability assessment framework. We will discuss how the assessment contributes to underpinning policies for integrated river basin management.

Speaker profile:

Huijuan Wu is a DPhil candidate in Engineering Science at the University of Oxford, having previously completed her MSc in Water Science, Policy and Management. Her current research is concerned with integrated assessment framework for large river basins, by using sustainability indicators and composite indices. Prior to Oxford, she worked with Halcrow, a leading environmental consultancy in the UK. She has actively been involved in climate change negotiations, has attended UNFCCC COP15 in Copenhagen and Rio+20, the UN Conference on Sustainable Development. She is also a freelance writer for the BBC Chinese service.

****

I look forward to a positive response from you. If you are unable to attend, I request you to nominate a colleague who works on similar issues.

Arunabha

RSVP to ceo.office@ceew.in by Friday, 6 September 2013.

APPENDIX III Assessment Results

III.1 LYR Sustainability Assessment Indicators Scores (1950 to 2010)

	Environmental Performance						Social Wellbeing							Economic Development				
Year	EP1	EP2	EP3	EP4	EP5	EP6	SW1	SW2	SW3	SW4	SW5	SW6	SW7	ED1	ED2	ED3	ED4	ED5
1950	0.47		1.00		1.00		1.00	0.97	0.88	0.09				0.00	0.00	0.02		
1951	0.64		1.00				1.00	0.97	0.86	0.09				0.00	0.00	0.02		
1952	0.44		0.83				1.00	0.95	0.84	0.10				0.00	0.00	0.03		
1953	0.48		0.67				1.00	0.96	0.82	0.11				0.00	0.00	0.04		
1954	0.72		0.60				0.83	0.97	0.80	0.12				0.00	0.00	0.05		
1955	0.66		0.70				0.67	0.96	0.78	0.13				0.00	0.00	0.05		
1956	0.12		0.80				1.00	0.95	0.83	0.13				0.00	0.00	0.06		
1957	0.09		0.67				0.89	0.96	0.83	0.14				0.00	0.00	0.07		
1958	0.64		0.50				0.79	0.80	0.84	0.15				0.00	0.00	0.08		
1959	0.49		0.53				0.43	0.79	0.84	0.16				0.00	0.00	0.08		
1960	0.28		0.57	0.36			0.88	0.29	0.84	0.16				0.00	0.02	0.09		
1961	0.82		0.60	0.43			1.00	0.40	0.84	0.17				0.03	0.04	0.10		
1962	0.52		0.97	0.41			0.80	0.58	0.84	0.18				0.03	0.04	0.10		
1963	0.54		1.00	0.28			0.98	0.79	0.84	0.19				0.03	0.04	0.11		
1964	0.68		1.00	0.07			0.92	0.81	0.84	0.19				0.03	0.04	0.12		
1965	0.27		1.00	0.29			0.43	0.96	0.78	0.20				0.03	0.04	0.13		
1966	0.59		0.70	0.02			0.99	0.72	0.77	0.21				0.03	0.04	0.13		
1967	0.80		0.83	0.00			0.86	0.70	0.75	0.22				0.03	0.04	0.14		
1968	0.82		0.67	0.09			0.32	0.85	0.73	0.22				0.03	0.05	0.15		
1969	0.03		0.37	0.20			0.69	0.73	0.71	0.23				0.19	0.12	0.16		
1970	0.16		0.27	0.04			1.00	0.81	0.69	0.24				0.19	0.12	0.16		

1971	0.27		0.00	0.13			0.91	0.78	0.67	0.25				0.19	0.12	0.17		
1972	0.51		0.00	0.35			0.98	0.80	0.65	0.26				0.19	0.12	0.18		
1973	0.32		0.00	0.08			0.98	0.81	0.63	0.26				0.19	0.12	0.19		
1974	0.20		0.00	0.35			0.77	0.71	0.61	0.27				0.19	0.12	0.19		
1975	0.84		0.00	0.09			0.97	0.84	0.61	0.28				0.19	0.13	0.20		
1976	0.82		0.33	0.22			0.24	0.91	0.59	0.29				0.19	0.14	0.21		
1977	0.43		0.53	0.05			0.39	0.94	0.58	0.29				0.19	0.14	0.22		
1978	0.51		0.37	0.15			0.84	0.73	0.57	0.30				0.19	0.14	0.22		
1979	0.73		0.40	0.22			0.96	0.71	0.55	0.36				0.19	0.14	0.25		
1980	0.27		0.37	0.38	0.63		0.97	0.81	0.54	0.41	0.80			0.19	0.14	0.28		0.45
1981	0.68		0.17	0.13			1.00	0.67	0.52	0.43	0.77			0.19	0.14	0.31		0.48
1982	0.72		0.40	0.34			0.27	0.90	0.51	0.46	0.73			0.19	0.14	0.34		0.50
1983	0.90		0.73	0.25			0.70	0.96	0.50	0.45	0.69			0.19	0.14	0.38		0.53
1984	0.82		0.70	0.19			0.76	0.97	0.48	0.45	0.65			0.19	0.14	0.41		0.55
1985	0.71		0.77	0.22			0.72	0.97	0.49	0.44	0.61			0.19	0.14	0.44		0.57
1986	0.41		0.60	0.25		1.00	0.80	0.89	0.50	0.49	0.57			0.19	0.14	0.45		0.58
1987	0.10		0.40	0.27			1.00	0.89	0.50	0.49	0.52			0.19	0.14	0.47		0.60
1988	0.27		0.27	0.14			1.00	0.77	0.50	0.48	0.47			0.19	0.14	0.47		0.62
1989	0.97		0.40	0.25			0.65	0.88	0.50	0.49	0.42			0.34	0.16	0.50		0.63
1990	0.43		0.00	0.33			0.97	0.90	0.46	0.50	0.47			0.34	0.16	0.52		0.65
1991	0.42		0.00	0.43			0.98	0.63	0.44	0.55	0.44			0.34	0.16	0.54		0.66
1992	0.27		0.00	0.21			0.96	0.50	0.42	0.57	0.41	0.80		0.34	0.16	0.56		0.68
1993	0.27		0.00	0.37			0.86	0.82	0.39	0.58	0.38			0.34	0.16	0.59		0.70
1994	0.26		0.00	0.19			0.90	0.68	0.37	0.60	0.35			0.34	0.16	0.63		0.72
1995	0.27		0.00	0.29		0.96	0.78	0.63	0.34	0.63	0.32		0.00	0.34	0.16	0.67	0.28	0.74
1996	0.36		0.00	0.22			0.93	0.48	0.32	0.65	0.29		0.29	0.34	0.18	0.70	0.35	0.76
1997	0.20		0.00	0.48			0.66	0.12	0.29	0.67	0.25	0.20	0.48	0.34	0.25	0.71	0.38	0.78
1998	0.32	0.29	0.00	0.40			1.00	0.13	0.19	0.68	0.22	1.00		0.34	0.25	0.73	0.38	0.79
1999	0.27	0.40	0.00	0.44			1.00	0.66	0.23	0.69	0.18	1.00	0.56	0.34	0.25	0.75	0.44	0.80
2000	0.10	0.39	0.00	0.53			1.00	0.88	0.25	0.70	0.25	0.80	0.39	0.50	0.29	0.76	0.59	0.81

2001	0.10	0.32	0.00	0.57			1.00	0.92	0.18	0.75	0.32	0.72	0.65	0.50	0.36	0.79	0.76	0.83
2002	0.22	0.19	0.00	0.47			1.00	0.90	0.20	0.80	0.22	0.56	0.64	0.50	0.37	0.82	0.76	0.84
2003	0.72	0.21	0.00	0.32			0.40	0.94	0.31	0.86	0.23	1.00		0.50	0.37	0.84	0.78	0.86
2004	0.47	0.27	0.00	0.59			1.00	0.95	0.37	0.88	0.20	0.72	0.94	0.50	0.44	0.86	0.82	0.89
2005	0.59	0.40	0.00	0.88			1.00	0.93	0.19	0.90	0.23	1.00	0.91	0.50	0.44	0.88	0.83	0.91
2006	0.79	0.42	0.03	0.89		0.82	1.00	0.96	0.26	0.91	0.27	0.36	0.99	0.50	0.45	0.90	0.82	0.93
2007	0.69	0.49	0.10	0.83			0.60	0.95	0.30	0.93	0.28	0.96		0.50	0.51	0.91	0.84	0.95
2008	0.44	0.46	0.27	0.88	0.37		0.80	0.98	0.19	0.94	0.27	0.89	1.00	0.50	0.51	0.93	0.85	0.97
2009	0.42	0.45	0.33	0.99			1.00	0.95	0.22	0.97	0.24	0.81	1.00	0.50	0.51	0.96	0.89	1.00
2010	0.74	0.48	0.36	0.77			1.00	0.97	0.21	0.98	0.25	0.71		0.50	0.51	1.00	0.91	0.99

III.2 UGR Sustainability Assessment Indicators Scores (2001 to 2010)

	Environmental Performance				Social Wellbeing				Economic Development			
Year	EP1	EP2	EP3	EP4	SW1	SW2	SW3	SW4	ED1	ED2	ED3	ED4
2001	1.00	1.00	0.97		0.58	0.00	0.50	0.99	0.20	0.74	0.35	0.89
2002	0.43	1.00			0.63	0.00	0.75	1.00	0.20	0.69	0.38	0.90
2003	0.83	1.00	0.76		0.65	0.00	0.50	0.33	0.20	0.68	0.42	0.85
2004	0.47	1.00			0.70	0.04	0.55	1.00	0.20	0.71	0.46	0.95
2005	0.50	0.62	0.86		0.70	0.10	0.65	0.92	0.18	0.81	0.55	0.95
2006	0.29	0.66			0.73	0.18	0.55	0.36	0.66	0.80	0.64	0.85
2007	0.97	0.75	0.86		0.75	0.26	0.75	0.37	0.55	0.77	0.67	0.88
2008	0.29	0.32			0.75	0.38	0.80	0.49	0.54	0.81	0.69	0.97
2009	0.00	0.36	0.86		0.78	0.50	0.90	0.00	0.54	0.93	0.74	0.89
2010	1.00	0.29		0.24*	0.83	0.65	1.00	0.49	0.54	0.94	1.00	0.93

*The score of the biodiversity indicator is for the year 2013