PRELIMINARY ENVIRONMENTAL FLOWS ASSESSMENT FOR THE LI RIVER

Prepared by the International Water Centre and Pearl River Water Resources Commission

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International WaterCentre Pty Ltd
PO Box 10907, Adelaide St
Brisbane, Qld, 4000
Tel: +61 7 31237766
Email: info@watercentre.org
www.watercentre.org

Australian Government
AusAID

INTERNATIONAL WATERCENTRE

Executive summary

This report documents an environmental flows assessment for the Li River, a tributary of the Pearl River in Guangxi province of the People's Republic of China. The report is designed as the basis upon which those responsible for water allocation and management can make decisions about trade-offs between environmental and human water use, with an understanding of the connections between important river assets and functions and the different aspects of the flow regime. An environmental flow defines the important flow components in terms of frequency, duration, timing, magnitude, and rate of change. These specifications allow a river manager to implement the recommended flows as a comprehensive flow regime, either by directing controlled flows to a river, or by preventing inappropriate diversion of flows from a river.

The assessment framework followed here relies heavily on existing knowledge. It is the same approach as that adopted in other pilot projects within the River Health and Environmental Flow in China Project and is similar to existing holistic approaches to the assessment of environmental flows used elsewhere in the world. The approach involves:

1) Dividing the river into reaches (in this case a single reach was examined)
2) Identifying the key ecological assets
3) Identifying the flow issues that affect each of those ecological assets
4) Establishing broad objectives
5) Using hydrologic and hydraulic models and analyses to specify the requirements for different flow components to meet those objectives, and
6) Consolidating the flows required to meet the different objectives into a single set of recommended flows.

The report draws on existing published literature concerning the environmental flow needs of the Li River, especially with respect to fish and vegetation, and combines this with analysis of existing hydrological and biological data to derive the flow objectives.

The report provides a preliminary (and minimum) set of environmental flow components that need to be provided – either through protection or augmentation of existing flows – to have some prospect of achieving the environmental flow objectives for the Li River set out in this report. The recommended flows generally consist of three flow components:

1) **Low flows**: enhancement of dry season base flows, to improve navigation, and prevent periods of poor water quality
2) **High flows**: the protection of existing wet season base flows, to maintain habitat necessary for fish reproduction, and
3) **Flow pulses**: the maintenance of dry and wet season flow pulses, to maintain riparian vegetation, to maintain habitat, and to support fish reproduction.

Details of the recommended flows are shown in Table 1. Each element of the recommended flow regime is linked to one or more flow objectives. These objectives relate to broader goals related to geomorphology, fish, vegetation, water quality, and tourism (i.e. navigation). The specification of flow components, particularly their magnitude, relies heavily on relationships between river hydraulics and river discharge. The flow volumes required are based on values calculated using a 1-dimensional hydraulic model, using 99 cross-sections. Table 1 includes three different flow values: the median estimate represents the flow volume that meets the objective at 50% of the cross sections, while the upper and lower bounds represent the flow required to achieve the objective at just one, or all of the cross sections respectively.

The recommendations are based on sound, but easily accessible information, and should undergo future refinement. The hydraulic model and the flow-ecology linkages used to underpin the recommendations need to be validated and the results should therefore be treated as a demonstration of the process that can be applied to identify important flow components. Further work to improve the understanding of the flow-ecology relationships in the river may allow for more sophisticated and refined flow recommendations.

Additional work is also required to evaluate the accuracy of the one-dimensional model that was used to estimate depths and velocities at each cross section, and the extent to which discharge variation affects the amount of the channel that remains wetted. In the future, application of 2D models may be more appropriate in rivers of this size. Further consideration of the rates of rise and fall, and the influence of river flows on water quality and floodplain vegetation is also recommended.

Finally, variability in river flows – whether between years, seasons or days – is an important natural characteristic of rivers. The recommendations from the current study focus primarily on identifying large and demonstrably important aspects of flow variation. Future work should focus on further evaluating these recommendations while at the same time considering other, potentially less obvious aspects of short-term flow variability. This will require local expert input from the disciplines of engineering, hydrology, fisheries management, floodplain and wetland ecology and water resource management, but broadly would follow a similar approach to that laid out in the current document.

Table 1. Summary of flow recommendations based on adopting the minimum discharge required to meet all of the flow objectives specified against each flow component. Flow objective IDs relate to *T (Tourism), F (Fish), V (vegetation), G (Geomorphology), WQ (Water quality). Note flow recommendations for Vegetation and Water Quality are incomplete. See report for details.

						Flow volume required (m^3/sec)		
Flow objective ID*	**Flow component**	**Mean annual frequency / duration**	**Inter-annual frequency**	**Timing**	**Rate of rise/fall**	**Med**	**Up**	**Low**
T1, T2, F1, F2, F3, V1, V2, WQ 1, WQ2	Low flow	Continuous	Every year	Sep-Feb	-	60	60	60
G1	Low flow pulse	1 per year	Every year	Mar-Apr	See Figure 10	100	750	20
F5, F7	High flow	Continuous	Every year	Apr-Sep	-	60	400	20
F6	High flow	Continuous	Every year	May-Juy	-	100	100	100
F4, F6, V3, G2, G3	High flow pulse	1-2 days followed by	Every year	Apr-Jun	See Figure 10	2000	2000	1000
		10-20 days		Apr-Jun	>1.2m in 12 hours	200	200	200

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Acronyms

ACEDP	Australia-China Environment Development Partnership
AusAID	Australian Agency for International Development
IWC	International WaterCentre
MEP	Chinese Ministry of Environmental Protection
MWR	Chinese Ministry of Water Resources
PRWRC	Pearl River Water Resources Commission

Chapter 1. Introduction

1.1. Background to this study

This is a report on work undertaken as part of the River Health and Environmental Flow in China Project (‘the project’), The project is one of a number under the Australia-China Environment Development Partnership (‘ACEDP’), which is a five-year, Australian Government, AusAID initiative with the objective of supporting and improving policy development in China in the area of environmental protection and natural resources management. The project aims to support those goals by strengthening China’s approaches to assessing and monitoring river health, and assessing the river flows required for achieving ecological health.

The Pearl River sub-project is one of three pilots under the project. The Pearl River sub-project includes both a river health assessment and an environmental flows assessment. The main objective of the work is to trial and document approaches to river health assessment and environmental flows assessment that are applicable to the the Li River specifically, and which also have potential for wider application in China.

1.2. Definition of environmental flows

A flow regime is the pattern of flows in a river, which can be thought of as comprising a variety of “flow components”. Flow components are usually identified in terms of their magnitude, timing, frequency, variability and duration of occurrence, and their role in supporting critical ecological and physical processes within the river corridor. Any flow regime will support a certain level of aquatic health. This applies to all rivers, regardless of whether a formal effort has been made to assess specific environmental flow needs.

In this study, the term “environmental flow” means a flow regime, fully specified through a scientifically-based process, which is associated with an expected level of river health. Thus, the term environmental flow refers to a description of a flow regime (and associated water volumes). In any river, the specified environmental flow may occur naturally within the existing flow regime, it may be implemented artificially through dam releases, or it may be implemented through reducing extractions of water. It is assumed that, to a certain degree, an environmental flow will maintain riverine goods and services that people rely on.

The most common understanding of an environmental flow, and the one adopted here, is that it is water that maintains healthy, functioning riverine ecosystems (i.e. river channel, immediate floodplain and estuary). While environmental flows are used to sustain both ecological and human values of riverine ecosystems, environmental flows are not specifically designed to support off-stream environmental assets or uses. For example, the specification of an environmental flow does not consider the effect of rainfall and runoff on catchment forests before water reaches a river, nor the value of water that is diverted from a river to irrigate urban parks and gardens. Irrigation is not a direct beneficiary of environmental flows because the supply of water to agriculture does not fundamentally rely on riverine ecosystems being healthy. The understanding definition adopted here is consistent with the ‘Brisbane Declaration on Environmental Flows’, proclaimed at the 10th International River Symposium and International Environmental Flows Conference, held in Brisbane, Australia, on 3--6 September 2007:

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

Recommended environmental flow regimes are not necessarily the ideal flow regimes for maintaining river health. Recommended environmental flow regimes must take into account operational constraints (e.g. the ability to supply and release the required amount of water at a particular point in time) and the needs of other river functions (e.g. often flood control, irrigation water supply, domestic water supply). Thus, recommended environmental flow regime options are but one of the considerations in determining the water allocation arrangements and actual flow regime of a river. An environmental flow regime is usually thought of as a specification of the minimum flow that will sustain a given level of ecosystem health at a low level of risk (i.e. the agreed ecosystem objective). The term “minimum flow” includes specification of baseflow magnitude and variability, the number and duration of flow pulses and floods, and the occurrence of cease to flow events in naturally intermittent streams. The regime may also be specified with upper limits on flows, because sometimes flows managed to suit non-environmental users are excessively high or aseasonal relative to the ecosystem requirements.

Environmental water requirements can be specified at a range of scales. At the basin planning scale it is usually sufficient to know the mean annual environmental water requirements (this is better termed an “environmental allocation”), while at the local scale it is necessary to know daily targets for flow magnitude, duration, timing, frequency and rates of change under a range of environmental conditions (such as during droughts, or wet years). This project provides information at the scale of detailed river operations.

1.3. Environmental flow assessment method

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

The method of environmental flows assessment used here is based on the framework proposed by Gippel & Speed (2010b). This framework will accommodate any form of environmental flow assessment, any analytical tools, any size river, any existing constraints (regulated or unregulated, pre-existing allocation), any existing or proposed river uses, and any balance of scientific or social input to the process (Figure 1). A detailed site-specific assessment would utilise all components of the framework, while a simpler assessment would undertake only a selection of the components. Omitting components of the framework will not prevent obtaining a result, but it will weaken confidence in achieving the expected outcomes and increase the risk of unexpected and unacceptable outcomes.

The first eight steps of the scientific input of the framework (Figure 1) were originally derived from existing proven environmental flow methodologies to suit a set of circumstances encountered in a study in Zhejiang province, China (Gippel et al. 2009a, 2009b). The approach was loosely based around the FLOWS methodology as used in Victoria, Australia (SKM et al. 2002), which is a derivative of the Building Block Methodology (BBM) that was first developed in South Africa (King and Louw 1998). The flow components of the BBM are also the foundation for the technical input to the DRIFT process, which was developed for a project in Lesotho (King et al. 2003a). A major difference between BBM and DRIFT is that DRIFT recombines flow components and their linked consequences to describe river condition associated with any flow regime of interest, while BBM provides only one flow option, designed to meet a particular set of objectives. DRIFT also considers social impacts of each defined state of river condition. The methodology followed by Gippel et al. (2009a, 2009b) is like DRIFT in that it: (i) generates a range of environmental flow options for analysis of the implications of future flow scenarios for the environment and other users, and, (ii) recognises the concept that a flow regime comprises definable, ecologically important, flow components. All of these methods belong to the holistic group of approaches, which are grounded on the ‘natural flow paradigm’, which states that discharge variability, as found in natural rivers, is central to sustaining and conserving biodiversity and ecological integrity (Richter et al. 1997, Poff et al. 1997, Bunn and Arthington 2002). This variability in discharge provides for biotic diversity, influences life history patterns, gives rise to lateral and longitudinal connectivity (e.g. access to floodplains, and open upstream-downstream passage), and is less favourable to invasive exotic species (Bunn and Arthington 2002).

The suggested generic framework (Figure 1) relies on five basic assumptions:

1. In most rivers, not all of the natural flow volume is required to maintain ecosystem health at an acceptable level (or ecosystem values at acceptable risk), so some portion of a river’s water can reasonably be used for non--environmental purposes.
2. Flow variability and the natural disturbance regime of a river are important for maintenance of river health.

3. The flow regime can be characterised in terms of a set of ecologically important flow components.
4. It is possible to predict the likely consequences for river health of partially or completely failing to provide the specified flow components.
5. Within the expected river health status to be achieved by the environmental flow regime, river health is not limited by non-flow related factors, such as physical habitat (shelter and substrate), food supply, water temperature, water quality, direct exploitation of biota (such as fishing), barriers to movement, and direct disturbance to biota (e.g. gravel extraction).

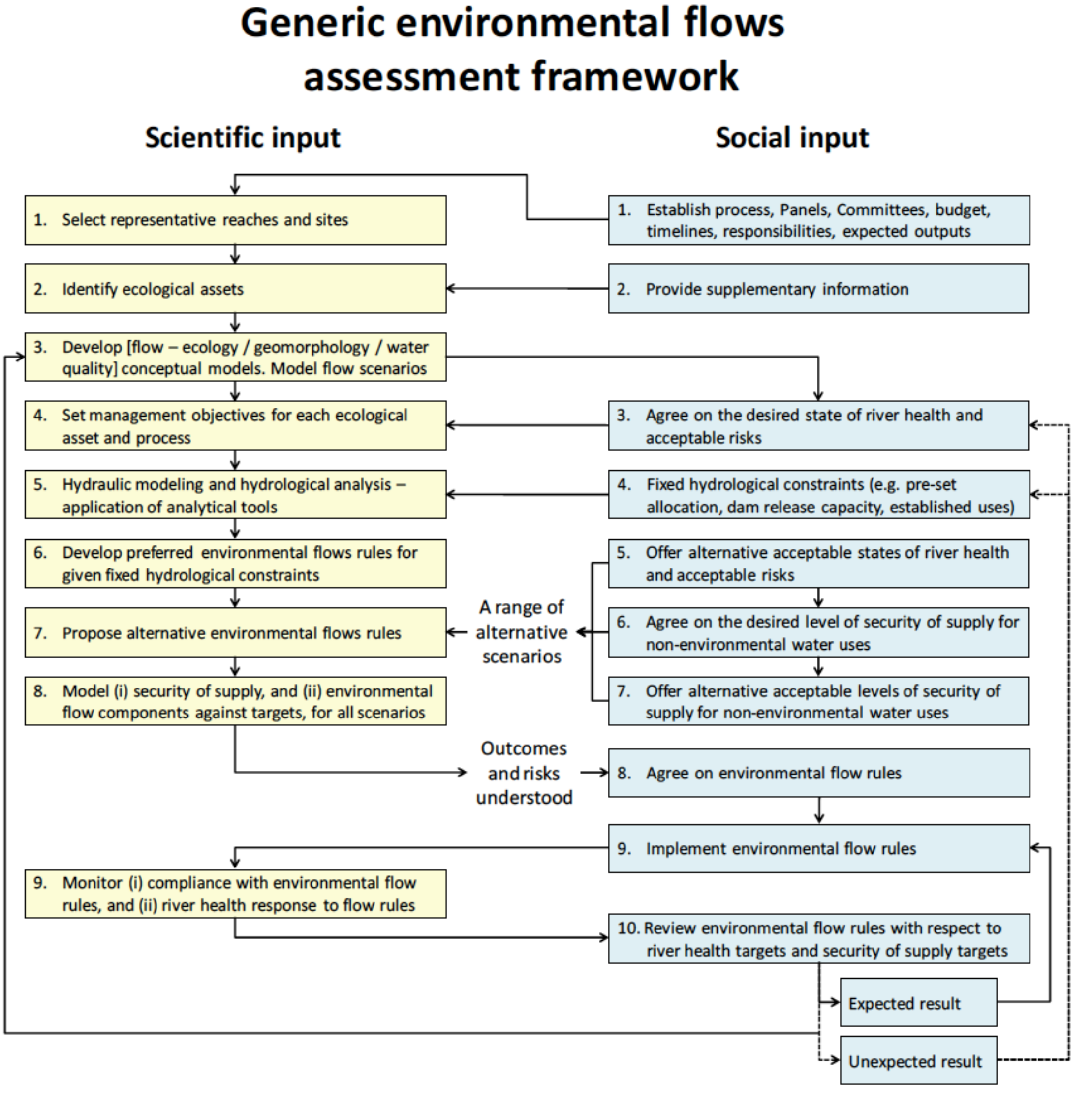


Figure 1. Generic environmental flow assessment framework. Source: Gippel & Speed (2010b).

With respect to the fifth assumption, environmental flow assessments are usually undertaken to address current or future (given the potential for future water resources development) impacts of flow alteration on river health. An assessment may also be undertaken for rivers in which non-flow related factors are the primary influence on river health. This is because it is technically possible to address the other limiting factors through management actions. Achieving river health often requires simultaneous management action on many fronts. It is not necessary for river health management to be undertaken in a step-wise fashion – sequentially addressing only the principal limiting factor. This is particularly the case with flow, because once flow is allocated to non-environmental uses it is difficult and costly to recall it for environmental use. Other limiting factors, such as water quality and physical habitat, can be improved at a later time without any serious impacts on the volumes of water available for non-environmental uses.

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

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

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

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

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

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

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

Thus, the method used here does not necessarily result in the recommendation of a single environmental flow regime that is considered “ideal” for the environment. Rather, it identifies important flow components that need to be considered in relation to specific ecological processes, and each having different implications for meeting river health objectives and utilitarian objectives. Balancing the flow needs of different users is undertaken by managers, together with other stakeholders as appropriate, using the science-based information provided by the environmental flows assessment. This is the process that ultimately decides the environmental flow regime that will be implemented in a river.

1.4. Objectives of this report

This report documents the scientific foundation for the environmental flow recommendations for the Li River. The report is designed as the basis upon which those responsible for water allocation and management can make decisions about trade-offs between environmental and human water use, with an understanding of the connections between important river assets and functions and the different aspects of the flow regime.

The environmental flows framework followed here relies heavily on existing knowledge, and shares the same specific approach as that adopted in the Yellow River pilot project (Gippel et al. 2011), which has similarities to approaches previously applied in China (Gippel et al. 2009b) and several other countries (SKM et al. 2002, King et al. 2003b). This document, together with that of Gippel et al. (2011), should be seen as useful reference material for those wanting to undertake similar work in other rivers.

1.5. Structure of the report

The report is structured to follow the main steps of the adopted framework (Figure 1). The method involved:

1. Dividing the river into reaches (in this case a single reach was examined).
2. Identifying the key ecological assets.
3. Identifying the flow issues that affect each of those ecological assets.
4. Establishing broad objectives. In the case of the Li River, the existing river management vision and objectives were adapted from the minutes of a meeting with local and regional river management staff (PRWRC and local government authorities) in January 2010.
5. Specifying the requirements for different flow components.

There is some published literature concerning the environmental flow needs of the Li River, especially with respect to fish and vegetation (Li et al. 2010, 2011). Findings from these studies (Li et al. 2010, 2011) were used in conjunction with findings from the river health assessment component of this project (Bond et al. 2011) and reanalysis of existing hydrological and biological data to derive the ecological flow objectives. This necessitated a thorough review of existing research on the river’s hydrology, geomorphology, water quality and ecology. Together with analysis of data, this information was used to establish environmental flow objectives that were associated with the health of the identified ecological assets.

The specification of flow components, particularly their magnitude, relies heavily on relationships between river hydraulics and river discharge. The hydraulic relationships are derived through modelling based on river morphology and are described in detail in Chapter 6.

Chapter 2. Site and Assets

2.1. Overview of the region

The Pearl River Basin is located in southern China and crosses five provinces – Guangdong, Guangxi, Yunnan, Guizhou, Jiangxi – as well as northeast Vietnam (Figure 2). The basin has a total area of approximately 400,000km^2 and consists of three main tributaries, the Xi Jiang ("West River"), the Bei Jiang ("North River"), and the Dong Jiang ("East River"). The river is about 2,200 km in length from the start of the Xi Jiang to the delta, making it China's third longest in length, and is the second largest by volume with an average discharge of 9,500 m^3/s.

Figure 2. Map showing the location of the Pearl River Basin in China. The Pearl River Basin extends inland from China's south-east coastline.

2.2. Li River

The environmental flow regime assessment work was conducted on the Li River, which forms the main stem of the upper reaches of the Gui River catchment, a tributary in the north central region of the Pearl River Basin (Figure 3).

Figure 3. Map of the Pearl River Basin showing the location of the Gui River catchment, of which the Li River is an upper tributary.

The Li River originates from the south of Laoshanjie in the east slope of Mao'er Mountain in Huajiang village, Xing'an County, Guangxi Zhuang Autonomous Region, and flows into the Lingqu Canal in the township of Darongjiang. According to historical records, the Lingqu Canal was dug in 219 BC with an overall length of 34 kilometres, to divert water from the Xiang River into Li River (whose name literally means diverting away some of the water of Xiang River). The Li River then flows through a number of cities and counties – Guilin, Yangshuo and Pingle before flowing into the Gongcheng River to become the Gui River. After flowing through Zhaoping and Cangwu, it merges with Xun River into the Xi River in Wuzhou City (**Figure** 4).

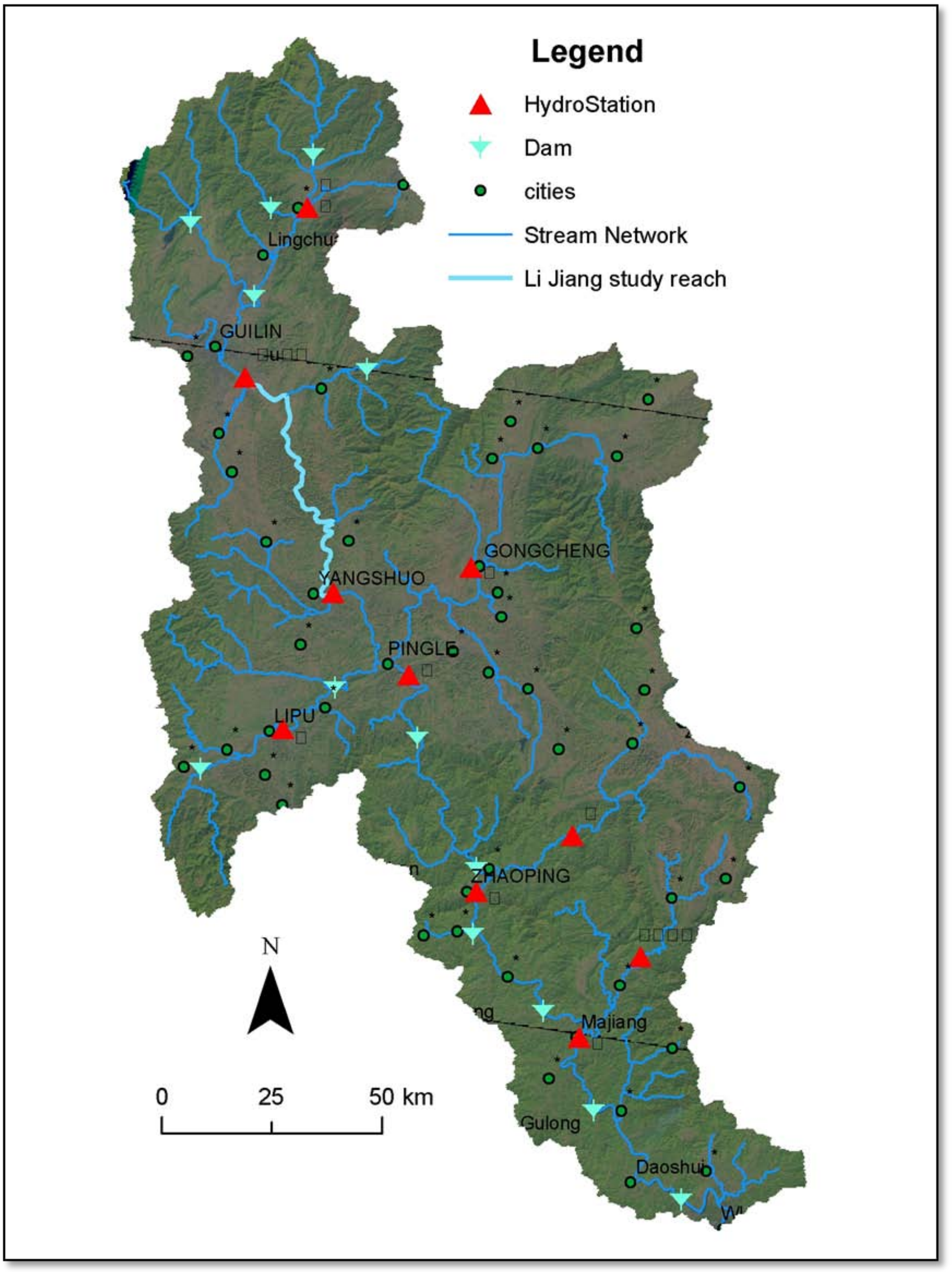


Figure 4. Figure showing LANDSAT image of the Gui catchment highlighting the Li River reach that was the focus of the study, together with major towns, gauging stations, water storages and river health assessment sites (see Bond et al. 2011).

2.2.1. Geology and land-cover

The landscape surrounding the Li River includes large areas of limestone, which give rise to a unique Karst landscape consisting of steep mountains surrounded by low-lying floodplains. While much of the floodplain has been developed, the steep mountainous areas remain largely forested; primarily broad leaved forest, but with some coniferous forest in the very upper parts of the catchment (Bond et al. 2011). The mountainous nature of the catchment, and high aesthetic values, has also meant that much of the native forest cover is still protected. This has presumably increased since the 1990s when a reafforestation program began. Anecdotally, while the upland vegetation is largely protected, there has been a substantial loss of floodplain wetlands in sections of the Li River floodplain due to agricultural development (Liu Wei, pers, comm.), and there is some concern relating to the effects on riparian vegetation from changes in river flows to maintain navigation for tourist boats on Li River during the dry season (Li et al. 2011). Overall however, in comparison to many other rivers in China (and elsewhere in the world), the Gui catchment still has a very high level of cover of native vegetation cover; ~48% forest and 36% grassland. Approximately 13% of the catchment is agricultural land (~2,285 km^2), and of this, approximately 1,700km^2 is irrigated. Less than 1% of the catchment is urbanised.

2.2.2. Climate

The Li River basin has a subtropical monsoon climate. The basin receives high amounts of rainfall, but it is spatially and seasonally variable ranging from an annual average of 2000~2400 mm in the north to an average of 1500~1600mm in the south-east. Rainfall during the wet season (March to August) accounts for more than 75% of the yearly rainfall, with less than 25% occurring during the dry season (September-February).

In the upper most parts of the catchment there is occasional snow during winter. However, temperatures are generally high, with an average annual temperature of 18.8 ° C, a maximum monthly average of 28°C (July) and minimum of 7.9°C (January). Daily temperatures range between -5.1-38.5°C. In the lower reaches the average temperature is about 19.7°C, with the highest average month temperature of 28.8°C in July, the lowest of about 9.2°C in January, and extremes ranging between -4.1- 40.0°C. Humidity in the Gui River basin is also high, averaging between 70-80% during the wet season and 6-13% in the dry season.

2.2.3. Hydrology

The hydrology of the river largely reflects the monsoonal climate; it has a distinctive summer wet season (April-September) and winter dry season (October-March). Reflecting seasonal rainfall, seasonal baseflow is markedly higher during the wet season, with frequent high flow spells occurring during this period. The hydrologic characteristics of the river are discussed in detail in Chapter 4.

2.2.4. Socio-economic situation

The Gui catchment has a population of approximately 5 million people, with the majority living in regional areas. Guilin and the Li River are famous tourist destinations, primarily as a result of the rare Karst landscape, which is most commonly viewed by tourists from boats travelling between Guilin and Yangshou. This major tourist trail constitutes the core of the study area along the Li River. The annual number of domestic and foreign tourists had exceeded 13 million by 2006 (PRWRPB, 2010).

Chapter 3. Environmental Flows Issues and River Management Policy Framework

3.1. Ecological assets

Rivers contain ecological assets in two main categories:

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

These two categories of assets are equivalent to the two functions of rivers described by Liu et al. (2006): natural function and social function, respectively. Intrinsic ecological assets are defined in terms of conservation values, with the most important, or “key” assets usually considered as those with the highest conservation value. Sometimes such assets are publicly identified by, for example, the 1971 Ramsar Convention that lists internationally significant wetlands, or listing as nationally or regionally important, rare, unique, representative or threatened assets. Other ecological assets might be regarded as important because they play a key role in ecosystem function. Ecological assets can be locations, species, or functions and processes. Ecological functions are physical, chemical and biological processes that support the ecological assets.

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

Environmental assets in the Gui River basin include drinking water source protection areas, nature reserves, water conservation forest reserves, wetland protected areas and river based tourism (sightseeing). Rivers are also a very important source of protein for many of the locals living within the catchment. Thus, the maintenance of healthy fish populations and the environmental conditions they depend upon are critical aspects of river health from a social perspective. More information on the ecological and social values of the Gui River catchment is provided in the background report (Bond et al., 2011). The basin does not include any specific areas of international importance such as Ramsar-listed wetlands.

The key location-based assets identified in this study are focused primarily in the channel and the surrounding floodplain between Guilin and Yuangshou. However, it is acknowledged that the broader catchment also includes some important wetlands that have become disconnected from their rivers through construction of physical barriers (dikes), flow regulation (which has reduced the frequency and duration of hydraulic connection), and land use change (such as direct conversion of native vegetation to cropland).

A meeting in Guangzhou in January 2010 of officials from the Pearl River Water Resources Commission, together with the project team, identified the following broad asset groups in the Gui River:

- Rare fish species
- Riparian wetlands
- Tourism
- Navigation
- Drinking water
- Hydropower

- Irrigation water

These groups of assets provided the starting point for assessing the environmental flow requirements for the Li River.

3.2. Flow related issues affecting river health

3.2.1. Lack of environmental flows below storages

The Gui River catchment includes three large cities, Guilin, Hezhou and Wuzhou, that extract water from the river. In 2008, water abstraction from the river totalled 4.026 billion m^3, among which Guilin 2.274 billion m^3, Wuzhou 167 million m^3 and Hezhou 1.585 billion m^3.

There are a number of large storages in the Gui River basin, including Qingshitan reservoir, Fuzi Mouth reservoir, Xiaorong River reservoir and the Chuan River reservoir, which focus on replenishing water in the Li River during the dry season, on flood prevention during the wet season, as well as localised power generation.

Despite high annual runoff totals, high seasonality in rainfall leads to a large gap between the runoff amounts in the flood season and the dry season. Lasting from September to February the next year, the dry season only accounts for 18.9% of the annual runoff. The actual measured average of lowest runoff months is only 5.9 m^3/s, or 4.5% of the average annual runoff. Insufficient adjustment capacity of upper-reach water storage projects means that during the dry season, serious water shortage problems occur. Noted impacts of this water shortage include periodic drying of the Li River, decreasing water quality, and the loss of navigation for tourism operators.

3.2.2. Changes to fish assemblages

Fish diversity and the abundance of important fisheries species (especially silver and bighead carp) have declined dramatically since the 1970s, primarily as a result of;

- construction of hydroelectric dams which have inundated spawning grounds and created longitudinal barriers to dispersal;
- alteration (in 1987) of release patterns from Qingshitan reservoir, which has reduced spawning opportunities (Li et al. 2011), and;
- high levels of fishing pressure which acts to dramatically reduce the number and size of reproductively mature fish. In the broader Pearl River basin the impacts of over exploitation of fish stocks on population viability is increasingly recognised, and there are extended fishing bans put in place each year during the spawning season. Whether these bans are effectively policed and achieving their goals is unclear.

3.3. Additional Threats

3.3.1. Pollutants (including sewage)

By degrading water quality, pollution can be a major threat to river health, although the 2011 assessment of river health (Bond et al. 2011) suggests that, with the exception of nutrient runoff, this is a secondary issue in the Gui River basin due to the low levels of industrial development. A 2005 survey conducted by the Pearl River Water Resources Protection Bureau found a total of 95 industrial and mixed sewage outlets (PRWRPB 2010). The main sources of water pollution are non-point source agricultural and urban runoff and sewage discharge. Most of the larger towns now have sewage treatment plants in operation. Specifically, there are four such plants in operation in Guilin and one in Wuzhou. The middle reach of the Gui River still has no sewage plants although Zhaoping was due to have a treatment plant completed in June 2010. While sewage treatment plants are now in operation in many of the larger towns and cities, there are also many localised sources of sewage discharge from smaller villages and settlements that will continue to have an impact on tributaries of the Gui River as well as the main channel itself. Sampling sites were intentionally selected to make sure these smaller streams were included as the cumulative impacts from small discharge sources are easily overlooked but can be significant.

3.3.2. Sand and Gravel Extraction

Over 30 gravel extraction plants along the Li River have been closed down in recent years, although 52 plants are still granted gravel extraction rights along 6 rivers, including the Gui River in Pingle County, the Xiang River across Quanzhou County and Xi'an County and the Zi River in Ziyuan County (PRWRPB 2010). Administration regulations and planning of river sand extraction have been developed in most cities and counties, which clearly identifies river course and areas available for sand extraction, as well as areas prohibited for extraction. As well as extraction of gravel for building requirements, illegal dredging for gold is also a common activity, with a recent China Daily report suggesting that over 400 illegal boats are active in the Gui River catchment, mainly located in Zhaoping and Cangwu reaches.

3.3.3. Invasive Animal and Plant Species

The most notable invasive alien species in the Gui River include the Apple Snail (*Ampullaria insularum*), Red eared sliders (*Trachemys scripta*), a type of turtle, and Canadian Goldenrod (*Solidago canadensis*) a highly invasive plant. The first two species were introduced to Guilin as food, but they have since been thought to have caused some ecological damage, although this is not well documented. In addition to terrestrial invasive plants like Canadian Goldenrod, there are at least two free-floating invasive plant species that occur in the Gui River, both of which are native to South America. Water hyacinth (*Eichhornia crassipes*) is listed as alien and invasive in China (Chu and Ding 2006), and Water lettuce (*Pistia stratioides*) is also invasive, though its native/alien status in China is unknown (http://www.issg.org). These species have the potential to form dense mats across the surface of the water, blocking out light and creating habitat suitable for mosquito breeding – a problem for human health. This is particularly likely in the warmer, sunnier months and in rivers that have high nutrient loads.

3.4. Objective setting process for environmental flows

The environmental flow objective setting process was based around meeting the flow needs of the ecological assets identified through stakeholder meetings and discussed in section 3.1. The major assets are certain wetlands and the river channel, but within these units are assets identifiable at a finer scale. These assets, such as certain species or communities, or physical and chemical processes, bestow the wetland and river channel assets with their intrinsic conservation values, and also their value in providing ecosystem services to society. These fine-scale assets can be evaluated with a framework that divides the ecosystem and its processes into the following linked categories:

- Geomorphology
- Water Quality
- Waterbirds
- Fish
- Macroinvertebrates
- Plants

The environmental flows framework requires experts from the various disciplines listed above to make individual contributions regarding issues and the objectives. These inputs are then merged to create a minimum set of objectives that jointly meet all of the requirements.

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

3.5. Reaches and sites for assessment

In environmental flows assessments, the river under investigation is usually divided into a number of reaches that are reasonably heterogeneous with respect to one or more ecological, hydrological, geomorphological and water quality attributes, and location of assets. The division into reaches simplifies the river, and allows different assessments to be made for different parts of the river in a structured way. The process produces a set of recommendations for each reach. Compliance of the actual flow regime against the recommended environmental flow regime is checked at relevant gauging stations. In the present study, the assessment was focused on a relatively homogeneous section of the Li River between Guilin and Yuangshou (ca. 85 km; Figure 4 & Figure 5). The homogenous slope of the river, coupled with the absence of any major tributaries influencing relationships between river discharge and hydraulics that suggested it would be appropriate to treat this section of the river as a single reach. This was further supported by observations during a boat trip down the river, coupled with an analysis of the hydraulic model, and the dispersed nature of ecological assets, including fish spawning grounds, along the entire reach. Thus, while it is an essential step to evaluate and identify discrete homogenous reaches for assessment (e.g. see Gippel et al. 2011), in the present case just a single reach and associated set of flow recommendations will be considered.

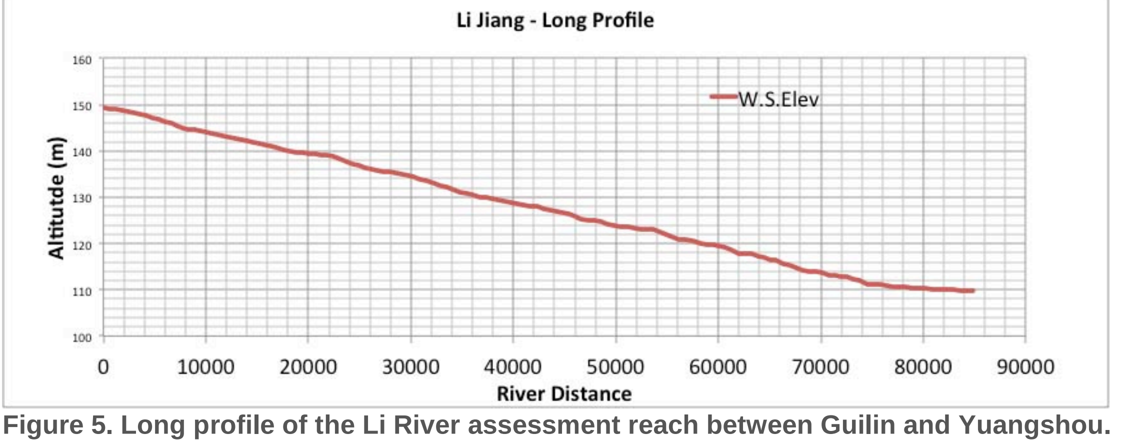


Figure 5. Long profile of the Li River assessment reach between Guilin and Yuangshou.

Chapter 4. Hydrology

4.1. History of river regulation

The largest and most hydrologically influential reservoir on the main stem of the Gui River is Qingshitan, which was completed in 1968 (constructed from1964-1968) to provide water supply and flood control. According to Li et al. (2011), since 1987 the reservoir has also been explicitly managed to increase navigability of the river between Guilin and Yangshuo, a section famous for its karst landscape and popular with large tourist boats. At present there are still insufficient flows during the late dry season and boat passage is often restricted to a shorter section of the river or must cease entirely. For this reason, several further reservoirs are currently under construction, which, when completed, will increase the minimum baseflows to 60 m^3/s.

4.2. Characterisation of environmental flow components

4.2.1. Rationale of flow components

Although the flow in a river varies continuously from nothing or low flow up to major floods, most conceptual models exploring the influences of flow variation on river ecosystems identify key flow components (parts of the flow regime) that serve important physical and biological functions (e.g. maintaining the channel morphology, sufficient minimum habitat during periods of low flow, or flow to stimulate fish spawning). Flow components fall into three main categories (Table 1). Flow components are the building blocks of environmental flow recommendations. When fully specified, a suite of flow components forms a flow regime that can be implemented by river operators to maintain river health at a certain level. The flow components have hydrological characteristics that require specification so that they can be implemented into a practical flow regime (Table 1).

The specification of environmental flows for different flow components are made with an (explicit or implicit) understanding that they would have a high probability of achieving their intended ecological objectives. Thus, certainty of achieving a high level of river health would likely require a suite of flow components with a high volume, while the suite of components required to achieve a modest level of river health would likely require less water. Thus, flow components can be specified in different ways to create environmental flow options with different expected river health outcomes and different implications for sharing available water resources among the various users. The specifications for flow components listed in Table 1 are the minimum requirements that would enable a flow regime to be implemented. Depending on the circumstances, many other details may be required in order to specify a set of practical operating rules that would allow implementation of the environmental flow regime as intended.

Table 2. Flow components that comprise the flow regime

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

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

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

This section of the report is concerned with compiling the information base describing the hydrology of the river (point 1 above).

4.2.2. Data availability

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

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

Table 17. Li River historical mean daily flow data considered in this project.

Reach	Gauge	Regulation phase	finish
Guilin-Yuangshou	Guilin	1958-1967	Pre-regulation
		1968-1986	Post-regulation (low baseflows)
		1987-2010	Post-regulation (augmented baseflows)

4.2.3. Flow seasonality and Water year

The Li River is characterised by a strongly seasonal flow pattern but with considerable monthly variation (Figure 6). For the purposes of describing the hydrologic characteristics, the water year traditionally ends with a low flow month, so that all the water from the high flow season is fully contained within a 12-month period. In this case, the month with the lowest mean discharge is regarded as the ideal start of the water year. However, from the perspective of environmental flows, the high flow and low flow seasons are considered to be of equal value, so it is desirable to fully contain the low flow and the following high flow season within a single 12 month period. Thus, for environmental flow studies the water year ideally begins on the first month of the low flow season.

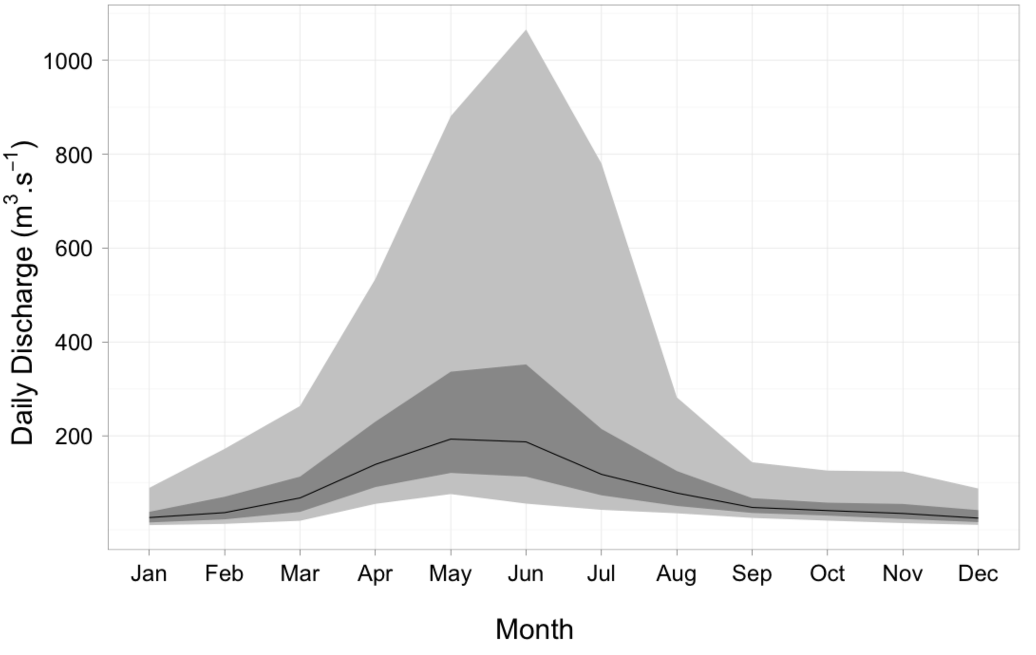


Figure 6. Plot of monthly flows at Guilin showing the median (black line), interquartile range (dark grey) and 5th-95th percentile flows (light grey). The light and dark grey shaded areas provide an indication of the range of flow variability.

Seasonality was examined for the period prior to and subsequent to the construction of Qingshitan Reservoir and both periods were found to be similar. In both cases September was the first month in the (average) driest 6-month period (Figure 7). The water year was thus considered to run from September to August, and was simplified into two periods; the high flow ‘wet’ season occurring from March-August, and the low flow ‘dry’ season running from September to February (Table 2).

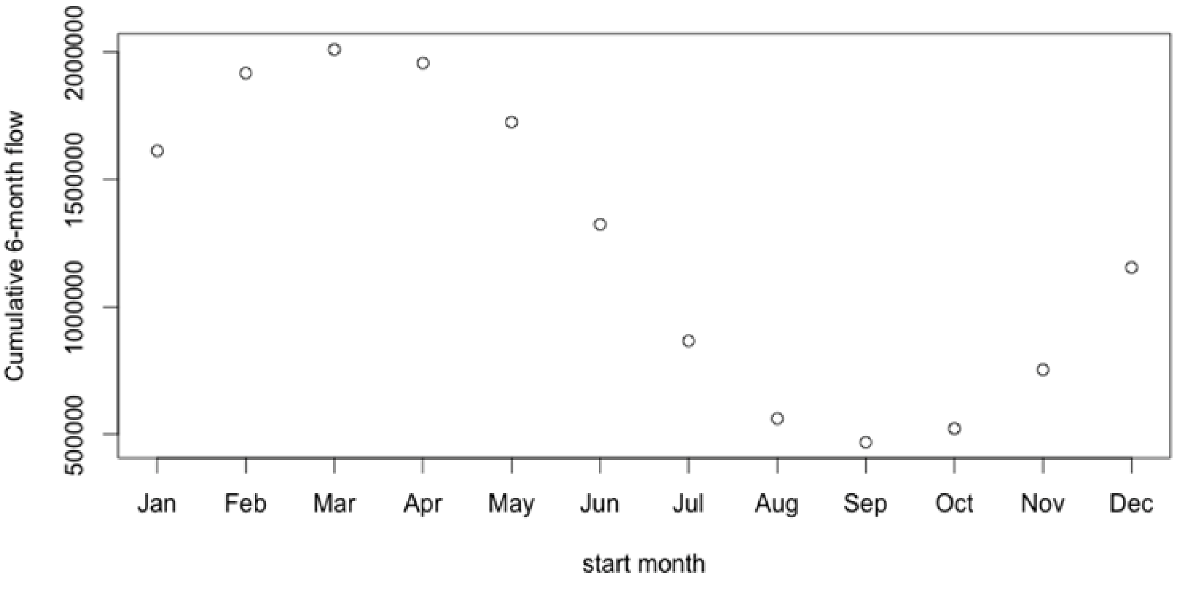


Figure 7. Plot showing cumulative 6-month flows starting in each month of the year. The plot shows that September is the starting month with the lowest cumulative flow for the next 6 months.

Table 3. Seasonal divisions adopted for the Li River.

Months	Season	Hydrologic descriptor
September – February	Dry season	Low flow
March - August	Wet season	High flow

4.2.4. Baseflows

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

$$f_k = \alpha f_{k1} + \beta(1 + \alpha)\,(y_k - y_{k1})$$

where f_k is the filtered quick response at the k^{th} sampling instant, y_k is the original streamflow, β is filter parameter set to 0.5 and α is a filter parameter set to 0.925. The filtered baseflow then equals y_k-f_k. The algorithm separates baseflow from total stream flow by passing the filter over the stream flow record three consecutive times (forwards, backwards, and forwards again). The justification for the use of this method rests on the fact that filtering out high frequency signals is intuitively analogous to the separation of low-frequency baseflow from the higher frequencies of quick flow (Nathan and McMahon, 1990). Baseflow separation was undertaken using River Analysis Package (Marsh n.d.).

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

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

Based on the observation by Li et al. that operation of Qingshitan Reservoir was modified in 1987 to augment dry season baseflows, baseflow volumes were examined separately for three periods; Pre-Qingshitan (1958-1967), Post-Qingshitan (1968-1986) and Post-baseflow augmentation (1987-2010).) (Figure 8). This comparison suffers from a very short period of pre-regulation data – arguably insufficient to adequately characterize the full range of baseflows, and on this basis it is hard to see any systematic overall change in median baseflows from pre- to post-regulation, particularly given the high inter-annual variability in median monthly flows overall (Figure 6). However, as suggested by Li et al. (2011) median baseflows have been higher during the middle of the dry-season (January) since 1987.

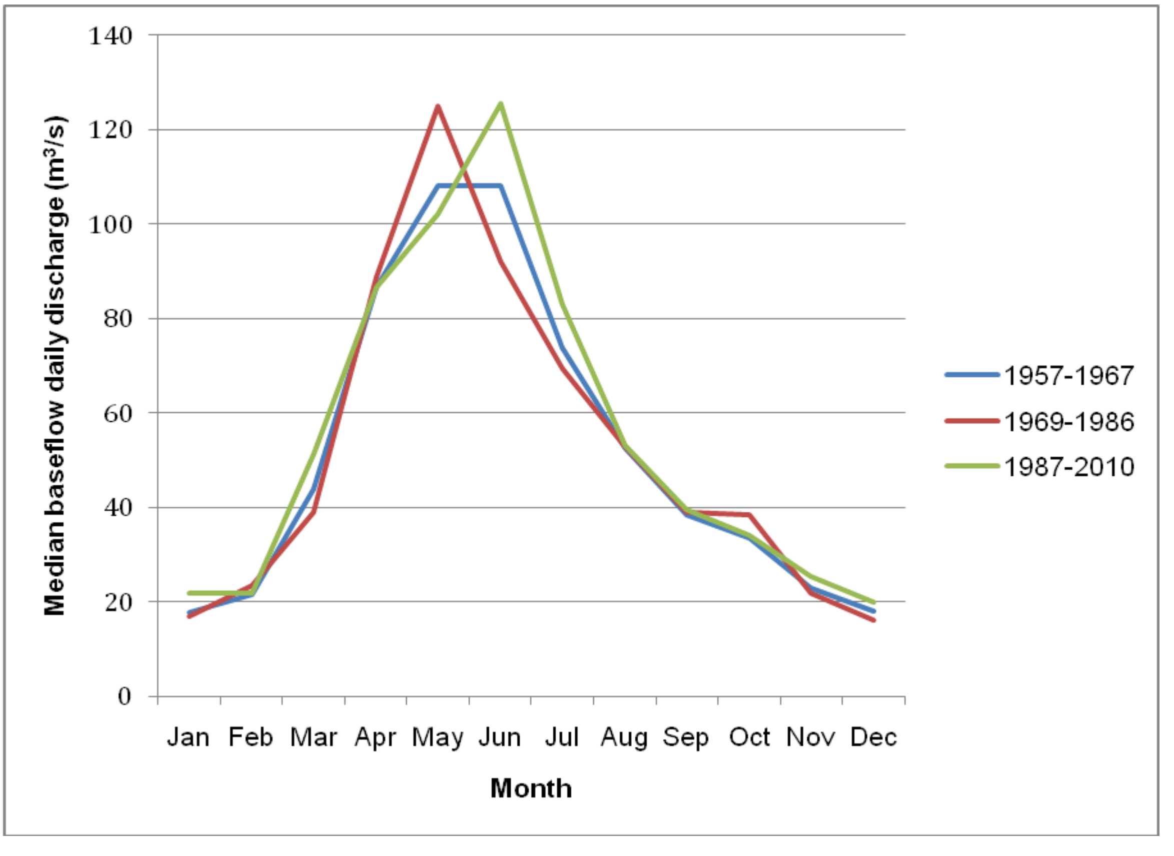


Figure 8. Median monthly baseflows at the Guilin gauge for three periods of reservoir construction and operation (see text for details).

4.2.5. Cease to flow events

No cease to flow events have been observed at Guilin in the historical time series and therefore cannot be analysed. Importantly however, given the lack of such flows historically, avoiding cease to flow events will be an important aspect of implementing a successful environmental flow regime into the future.

4.2.6. Flow events (pulses and floods)

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

In undertaking spells analysis it is necessary to consider event independence. For example, two spells might occur close together in time, separated by only a minor dip below the discharge threshold. From an ecological, chemical and geomorphological perspective this may not result in any significant disruption to the processes associated with flows above that threshold. In this case, the two spells would not be considered independent, but rather as a single continuous spell. In this study, event independence was defined as requiring a minimum of 7 days between instances when discharge exceeded the threshold. This is an arbitrary definition; refinement of this definition would require very detailed research to determine the time period between spells associated with a significant interruption to the processes of interest, but may be relevant for example to maintaining continuous transport of fish eggs, for which even short periods of flow below their entrainment threshold may increase mortality .

Spells analysis was undertaken across a range of flows and spells were characterized separately for the wet and dry season periods and for each of the regulation phases (Figure 9). Overall, high flow spells (above a given percentile) were higher in the wet season than in the dry, but also of shorter duration. There were no discernible differences between the pre-regulation and post regulation phases (Figure 9).

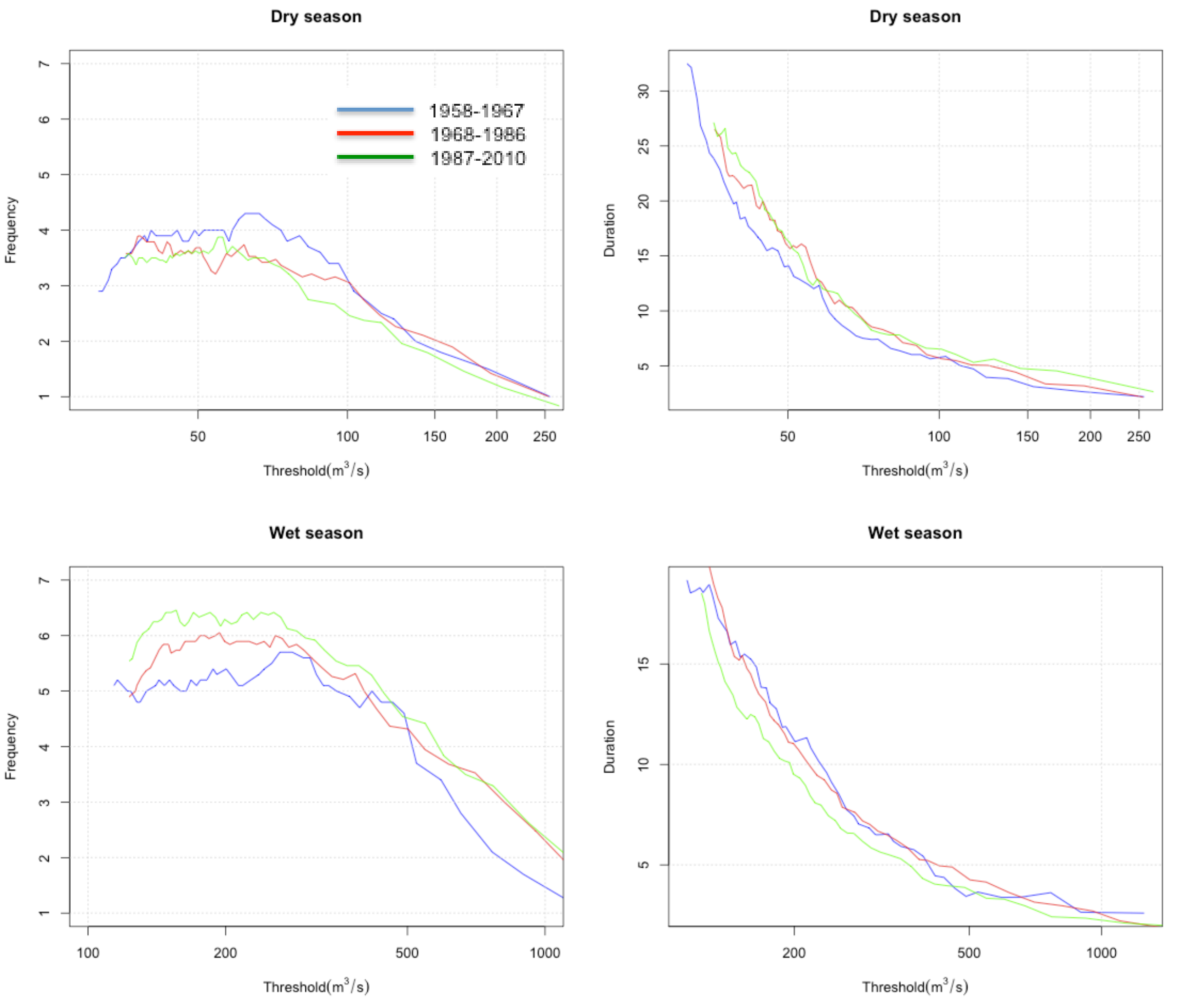


Figure 9. Results of spells analysis showing the characteristics (in terms of frequency and duration) of flows above different thresholds (m^3/s) during the dry and wet season respectively.

4.2.7. Rates of rise and fall (natural and regulated)

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

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

Rates of rise and fall were characterised for 24 discharge classes. Within each class, the 90th percentile of rise and fall was calculated. Rates of rise and fall were related to the discharge from which the discharge rose, or fell (i.e. *not* the discharge to which it rose to, or to which it fell). The higher the discharge the higher are the rates of rise and fall, with the rates related to discharge by a power function (Figure 10). In general, the rates of rise are faster than rates of recession, particularly at moderate discharges. Overall rates of rise and fall were similar for the three periods examined, pre-Qingshitan, post-Qingshitan and post baseflow augmentation, suggesting that (based on a short-period of pre-regulation data), the construction of Qingshitan reservoir has had no obvious impact on rise and fall rates.

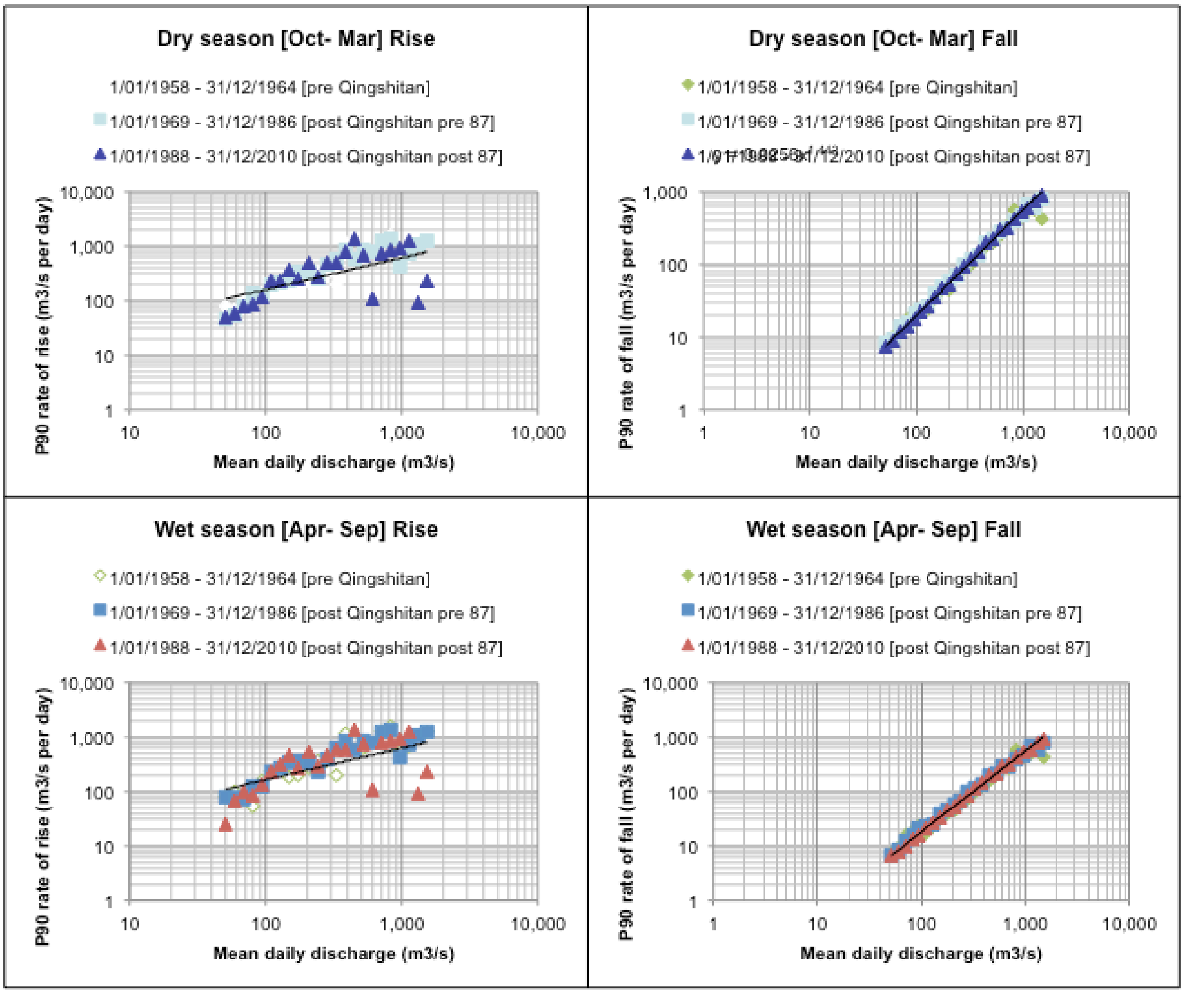


Figure 10. Rates of rise and fall at Guilin calculated for the wet and dry seasons respectively.

Chapter 5. Environmental flow objectives

The standard approach to setting environmental flow objectives is to separately consider the major ecosystem components that are related to the key river assets and functions (see section 1.3) and that are affected by flow and by one another. Separately specifying the environmental flow objectives for each ecosystem component simplifies the task, but can also mask the fact that these components are often interlinked, and depend on one another for their ongoing maintenance and functioning. The best way to establish these linkages and feedbacks is to develop a conceptual model linking the various components together. For example, fish that require deep pools or shallow riffle habitats depend on the maintenance of pool-riffle sequences, a geomorphic process that is itself flow dependent. Thus, while the geomorphic processes will have objectives established separately from those for fish, the achievement of the fish objectives will not be possible without considering the geomorphic objectives. This is not necessarily a complex issue to deal with, it simply requires that the various sets of objectives are considered together, and it is a simple task to also identify any 'dependencies' in other categories. This becomes most important if decisions are made to modify the complete set of recommendations, for example to try and reduce the overall environmental water allocation.

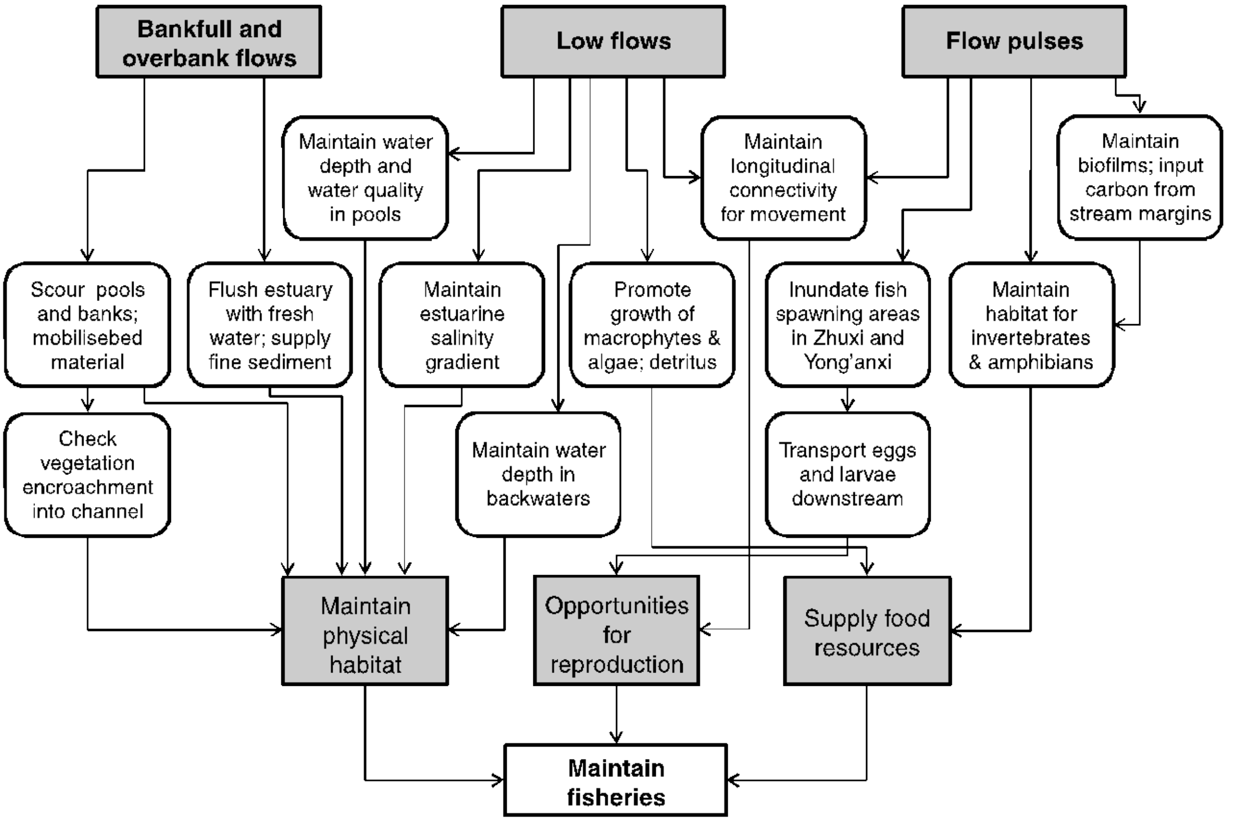


Figure 11. An example of a conceptual model linking various ecosystem components. Such models can be important tools to guide the establishment of the various flow objectives for each ecosystem component, and to ensure the necessary dependencies are maintained even where not specified directly. From Gippel et al. (2009)

5.1. Geomorphology

There is a general belief among river ecologists that high physical heterogeneity delivers greater diversity of habitats, which is beneficial to the biota (e.g. Kemp et al., 1999; Jowett and Duncan, 1990; Dollar, 2000; Chessman et al., 2006). Bartley and Rutherfurd (2005 p.39) summarised that:

"…*physical diversity and heterogeneity in streams is known to correlate well with biological diversity (e.g. Chisholm et al., 1976; Downes et al., 1998; Gorman and Karr, 1978; Ward et al., 2001) and reduced surface roughness and heterogeneity can in turn reduce species diversity, population abundance and recruitment (McCoy and Bell, 1991; Kolasa and Rollo, 1991). Thus, physical diversity is acknowledged as one indicator of stream health (Norris and Thoms, 1999) and diversity of habitat*."

River health is also dependent on the dynamic nature of the physical environment (Richards et al., 2002). Disturbance is widely recognized as a key process regulating riverine ecosystem structure and function (Resh et al., 1988; Townsend, 1989; Poff et al., 1997; Lake, 2000). Disturbance can be caused by hydrological events, but also by associated geomorphological events, such as bed and bank instability. For example, Florsheim et al. (2008) found that bank erosion is an important component of the natural disturbance regime of river systems and is integral to long-term geomorphic evolution of fluvial systems and to ecological sustainability.

A diverse physical habitat accommodates a wide range of preferences and tolerances of hydraulic conditions of biota. Also, physical irregularity potentially provides cover, and offers refugia at times of high flows when intolerably high velocities and shear stresses may occur in the main body of the flow. Consideration of fluvial geomorphology is important in environmental flow assessments because the health of the biota is reliant on the presence of a certain distribution of physical habitat in space and time. The flow-geomorphology-ecology relationship is underpinned by three fundamental concepts:

1. A spatially diverse physical environment will give rise to a spatially diverse range of hydraulic habitats at any time,
2. A hydrologically dynamic flow regime generates variability in the pattern of hydraulic habitat available over time by activating the full range of physical diversity present in the entire channel and floodplain, and
3. Channel dynamism gives rise to diversity of the physical environment.

Of these, it can be assumed that the first two are implicitly covered by flow-ecology objectives, which express the need for a certain variability and area of physical habitat to be available at certain times to provide for the needs of the ecological assets. Geomorphological flow objectives then centre on maintaining channel dynamism.

Ecologically-positive channel dynamism is associated with the processes of: creation of a range of channel forms (e.g. benches, bars, undercuts, pools and riffles) through sediment supply, transport and deposition processes (e.g. Yarnell et al., 2006; McBain and Trush, 1997); bank erosion (e.g. Florsheim et al., 2008); bed material mobilisation (e.g. Reiser et al., 1985; Gippel, 2001a, Dollar, 2000; Schmidt and Potyondy, 2004); flushing of fine sediment from the bed surface and hyporheic zone (e.g. Rowntree and Wadeson, 1999; Hancock and Boulton, 2005); vegetation succession in association with geomorphic disturbance (e.g. Hupp and Osterkamp, 1996; Richards et al., 2002); and large woody debris dynamics (e.g. Gippel, 1995; Montgomery et al., 2003; Lester and Boulton, 2008).

The common geomorphological objectives for environmental flows listed by Wilcock et al. (1996) are generally agreed by others (e.g. Hill et al., 1991; Brookes, 1995; McBain and Trush, 1997; Brizga, 1998; Gippel, 2001b). A comprehensive list of objectives includes:

1. Removing fine sediment from pools used for rearing habitat (in streams where pools are a distinctive characteristic).
2. Removing fine sediment from gravel and cobble substrates used for spawning, juvenile cover and invertebrate food production (in streams with coarse-bed material).
3. Entrain coarse sediment on the bed surface, permitting the removal of subsurface fine material

and producing a loose structure (in streams with coarse-bed material).

4. Entrainment of sediment through the active channel to prevent the establishment of mature vegetation and thus preventing a corresponding loss of aquatic habitat and channel capacity. Depending on the relative resistance of the bed material and the strength of the plants, the same effect might be achieved through direct flow damage to, or removal of, vegetation.
5. Erosion of the riverbank to maintain topographic diversity and provide a supply of coarse sediment and large wood (in streams where coarse sediment and large wood are characteristic).
6. Scouring sand from pools and maintenance of pool-and-riffle morphology (in streams where pool-riffle morphology is a distinctive characteristic).
7. Maintaining active channel width and topographic diversity.
8. Maintaining valley-scale features: channel pattern (straight, meandering, braided, anastomosing) and overall dimensions, and floodplain features such as wetlands.

Methods for estimating the flows required to achieve the above objectives can be found in the literature (e.g. Dollar, 2000; Gippel, 2001b; Schmidt and Potyondy, 2004). The methods fall into the categories of rules of thumb, mimicking natural flows, and empirical and semi-empirical sediment transport equations. Rules of thumb should be reserved for cases lacking hydraulic and sediment data; as a starting point, the frequency, duration and rate of rise and fall of events to meet geomorphological objectives can be based on the characteristics of such events as they occurred in the unimpaired flow regime; and, provided sufficient hydraulic and sediment data are available, the flow magnitudes required to meet some geomorphological objectives can be derived using established equations.

Given that a number of cities, towns and villages are located along the margins of the Li River, a high magnitude overbank valley forming flow of the order of 10 – 25 year average recurrence interval (to achieve Geomorphological objective #8) was not included in the objectives. Objective #5 was not high priority for the Li Jiang because for the majority of its course the banks are fortified by stone lining. Stable banks protect adjacent villages, farmland and the established natural riparian vegetation zone (which in places is narrow) from river migration.

In terms of hydraulic and hydrological requirements, geomorphological objectives #3, #4, #6 and #7 were lumped on the basis that they all would be met by mobilisation of the coarse bed material. The flow magnitude required to meet these objectives was determined using two groups of methods. The first was a hydrological rule of thumb, and the second was calculation of the critical shear stress for bed material mobilisation.

Schmidt and Potyondy (2004) suggested that in streams with gravel and cobble beds, the bed material would be fully mobile at around 80 percent of bankfull discharge, while 60 percent of bankfull discharge would mobilise sand beds. Schmidt and Potyondy (2004) defined bankfull by rule of thumb as the 1.5 year average recurrence interval (ARI) discharge. At Guilin, the partial duration series 1.5 year ARI flow is 1,750 m^3/s and the annual series 1.5 year ARI flow is 1,547 m^3/s. Of these, the estimate based on the annual series is consistent with the rule of thumb suggested by Schmidt and Potyondy (2004).

In natural cobble and gravel bed streams with a range of particle sizes present, the theory of equal mobility predicts that most of the grain sizes begin moving at nearly the same discharge. This does not imply that the entire bed surface moves at the one time, but that, at any instant, the bed load may consist of a range of particle sizes, and the bed selectively unravels from different locations as discharge increases (Gordon et al., 2004, p. 190). The critical shear stress (τ_c , in N/m^2), is the shear stress required to set bed particles in motion, represented by the Shields (1936) equation:

$$\tau_c = \theta_c \, g \, d_i \, (\rho_s - \rho) \qquad (1)$$

where,

θ_c θ_c = dimensionless critical Shields stress

g = acceleration due to gravity (9.8 m/s^2)

d_i d_i = grain size of particles (m)

ρ_s ρ_s = particle density (2,650 kg/m^3 for dense minerals)

ρ = water density (1,000 kg/m^3)

For particles to move, the actual shear stress (τ_b) must exceed the critical shear stress (τ_c).

There is considerable debate in the literature concerning the appropriate values of θ_c and d_i to use in the Shields equation (Gordon et al., 2004, p. 194). Buffington and Montgomery (1997) compiled 8 decades of flow-competence work and found that θ_c values ranged from 0.03 to 0.07. Andrews (1983) suggested a minimum θ_c value of 0.02 for gravel-bed rivers. Reviews by Miller et al. (1977) and Yalin and Karahan (1979) both reported that θ_c approaches a constant value of 0.045 for coarse particles (diameter > 10 mm). Andrews (1983) estimated that the dimensionless critical Shields stress could be estimated by:

$$\theta_c = 0.0834 \left(\frac{d_i}{d_{50}}\right)^{-0.872} \quad (2)$$

In this case, d_i would be the statistic selected to represent the armour layer and d_{50} is the median diameter of the sub-surface layer.

When estimating critical shear stress for a mixed-particle size bed material, median diameter (d_{50}) is often used as the representative diameter. However, as noted by Dollar (2000), several studies have pointed out that the coarse grain fraction must be entrained before the whole bed can become fully mobilized and unstable (Carling, 1983). Olsen et al. (1997) used d_{84} as the critical particle size for mobilisation of armoured gravel beds. If the armour layer is very well-sorted and compacted, a sample of randomly selected stones would tend to return only large surface stones, in which case it would be appropriate to use d_{50} to represent the armour layer. In the case of a frequently mobilised bed with a wide range of particle-sizes present it would be reasonable to use d_{84} to represent the armour layer. The bed material of the Li River showed evidence of frequent mobility (clean surfaces, and lack of embeddedness), and a reasonably wide range of particle sizes were present.

On the basis of the above discussion, for the Li River, five different parameter values were used in the basic Shields equation (1) to predict τ_c: 1. $\theta_c = 0.045$ and $d_i = d_{50}$; 2. $\theta_c = 0.02$ and $d_i = d_{50}$; 3. $\theta_c = 0.045$ and $d_i = d_{84}$; 4. $\theta_c = 0.02$ and $d_i = d_{84}$; and, 5. using equation [Eqn 2] to derive θ_c, with $d_i = d_{84}$.

Egiazaroff (1965) derived a formula for the critical shear stress for a sediment mixture:

$$\tau_c = \frac{{}^2/_3\, \theta_c \; g \; d_i \; (\rho_s - \rho)}{\left[\log\left(19 \frac{d_i}{d_{50}}\right)\right]^2} \quad (3)$$

where,

d_i d_i = particle size of interest, or d_{84} in the case of the armour layer

d_{50} d_{50} = median particle size of the sediment mixture

θ_c θ_c = selected as 0.06

Komar (1987) modified the original Shields entrainment expression to account for a natural mixed-particle size bed, to derive the flow-competence equation:

$$\tau_c = \theta_c \, g \, (\rho_s - \rho) \, d_{50}^{0.6} \, d_{max}^{0.4} \qquad (4)$$

where,

$d_{\max}$ □ d_{max} = the maximum diameter of the sediment mixture

θ_c θ_c = selected as 0.045

The exponent values 0.6 and 0.4 come from data obtained in streams where $d_{max}/d_{50} \leq 22$ and particle diameter ranges were 10 to 100 mm. When Lorang and Hauer (2003) applied the equation of Komar (1987) to 33 high gradient (≥ 0.002 m/m) gravel/cobble-bed (d_{84} = 35 - 1,000 mm) rivers in New Zealand [using data from Hicks and Mason (1991)], they found that the value of 0.045 for the dimensionless critical Shields stress (θ_c) predicted that the beds of most streams would be stable at bankfull, and a more appropriate value of θ_c was 0.02.

Julien (1995) presented equations for critical shear stress that were a function of the angle of repose of the particles ($\emptyset$):

$$\tau_c = 0.25 \, d_*^{\,-0.6} g \, (\rho_s - \rho) \, d_i \, \tan\emptyset \qquad \text{(for silts and sands)} \qquad (5)$$

$$\tau_c = 0.06 \, g \, (\rho_s - \rho) \, d_i \, \tan\emptyset \qquad \text{(for gravels and cobbles)} \qquad (6)$$

where,

$$d_* = d_i \left[\frac{(SG-1)\, g}{\upsilon}\right]^{1/3} \qquad (7)$$

and where,

SG = specific gravity of the sediment

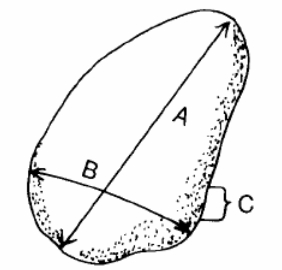
υ = kinematic viscosity of water (1×10^{-6} m^2/s)

The above review suggests nine versions of the critical shear stress approach:

1. The original Shields (1936) equation [Eqn 1], with $\theta_c = 0.045$ and $d_i = d_{50}$
2. The original Shields (1936) equation [Eqn 1], with $\theta_c = 0.02$ and $d_i = d_{50}$
3. The original Shields (1936) equation [Eqn 1], with $\theta_c = 0.045$ and $d_i = d_{84}$
4. The original Shields (1936) equation [Eqn 1], with $\theta_c = 0.02$ and $d_i = d_{84}$
5. The original Shields (1936) equation [Eqn 1], using equation [Eqn 2] to derive θ_c, with $d_i = d_{84}$.
6. The modified Shields (1936) equation of Egiazaroff (1965) [Eqn 3]
7. The modified Shields (1936) equation of Komar (1987) [Eqn 4], with $\theta_c = 0.045$
8. The modified Shields (1936) equation of Komar (1987) [Eqn 4], with $\theta_c = 0.02$, after Lorang and Hauer (2003), with $SG = 2.65$
9. The equations presented by Julien (1995) [Eqn 5, Eqn 6 and Eqn 7]

Pebble count is the most popular approach to sampling wadeable gravel/cobble bed streams (Gordon et al., 2004, p. 105). The original method was described by Wolman (1954). This involves walking along a transect and stopping at a consistent interval and measuring the particle located closest to the toe of one's boot. The particle is selected as the first one encountered by a metal rod inserted vertically to the bed at the point of the toe of the boot. It is recommended to sample at least 100 particles. To speed up the process, an experienced operator might be able to dispense with the rod, and 100 particles can first be collected in the stream and then stockpiled and measured on the bank. The dimension measured is the B-axis (Figure 12). If sampling multiple sites, it is best to consistently sample bed material from the same channel form, such as riffle crests. The Li River is too large to sample riffle crests, even at times of low flow, so samples were taken from exposed point bars or lateral bars (free of vegetation). Bed material was sampled at four sites along the river. The particle size data were converted to distributions of percent finer by weight (in phi classes), corrected for bias in sampling using the method of Leopold (1970) (Figure 13), and the required particle size statistics were derived from these distributions (Table 3).The Folk and Ward (1957) sorting coefficient indicated that the bed material was moderately to well sorted (Table 3).

Critical shear stress was estimated using the above listed nine methods, and the average calculated. Then a range of critical shear stress was determined after first rejecting the lowest and highest values (extreme values) (Table 3).



A is the longest axis (length)
B is the intermediate axis (width)
C is the shortest axis (thickness)

Figure 12. The three axes of a pebble in a stream bed.

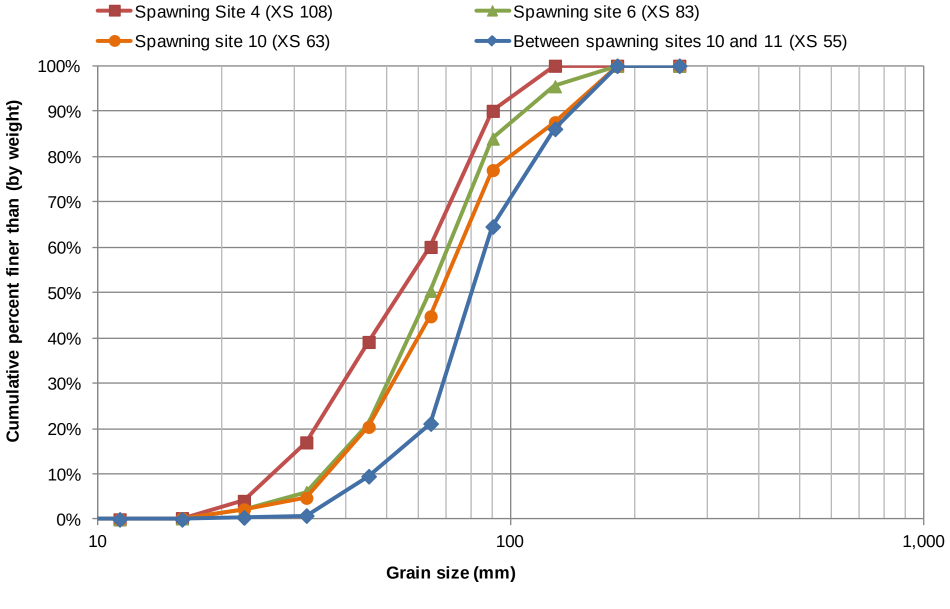


Figure 13. Particle size distribution of surface bed material in the Li River at four sites.

Table 4. Bed material size distribution statistics, and estimated critical shear stress for particle mobilisation.

Site	d_{50} (mm)	d_{84} (mm)		Sorting Coeff. (S)	Critical shear stress (τ_c) (N/m2)		
				Mean	**Lower**		**Upper**
Spawning site 4	54.2 (v. coarse gravel)	84.4		0.69 (mod. – well)	44.7	24.1	71.2
Spawning site 6	63.7 (v. coarse gravel)	90.7	0.61 (mod. – well)	50.9	29.3		76.5
Spawning site 10	67.7 (small cobble)	113.9	0.72 (mod.)	58.2	30.8		96.1
Between spawning sites 10 and 11	80.6 (small cobble)	123.8	0.61 (mod. – well)	65.9	35.3		104.4

Geomorphological objective #4 concerns prevention of the establishment of mature vegetation that could lead to channel contraction, by binding the bed sediments and offering low velocity zones for increased deposition of sediment. There are three main groups of vegetation that are usually considered in this context: trees and shrubs, herbs, and macrophytes. Trees, shrubs and herbs generally colonise the riparian areas and edges, and would tend to migrate towards the centre of the channel under a reduced flow regime. Macrophytes are rooted aquatic plants that can be emergent, submergent, or floating. Macrophytes provide cover for fish and substrate for aquatic invertebrates and algae and act as food for some fish (Carpenter and Lodge, 1986; Caffrey et al., 1999). However, if nutrient and light levels are elevated and flow velocities reduced, macrophytes can increase in dominance potentially colonising the entire stream channel, reducing the availability of other habitat types, such as deep and fast water, and clean gravel and cobble substrate, and also lowering dissolved oxygen levels at night (see Caffrey et al., 1999). Guscio et al (1965) reported reductions in the design channel capacity of up to 97 percent in a channel choked with macrophytes.

Macrophyte growth is a function of numerous factors, but water flow is known to be a prime factor (Franklin et al., 2008). The effects of flow on macrophytes are usually considered in terms of the hydrological regime (frequency of disturbance and duration of stable flow conditions) and velocity (which is associated with mechanical damage and uprooting). Long periods of stable baseflow may encourage invasion by macrophytes; for example, in Australia, *Typha* spp. are associated with stable water levels typical of regulated rivers (Mackay and Marsh, 2005). Riis and Biggs (2003) found that significant macrophyte development in New Zealand rivers was restricted to streams which experienced an average of less than 13 flood events per year (i.e. events exceeding 7 times the median discharge magnitude). In sandy substrates, the important flood events may be of a lower magnitude than this (Riis et al., 2008). Periods of low flow can also keep macrophytes in check (Franklin et al., 2008). Both the abundance and diversity of macrophytes are stimulated at low to medium velocities, with growth being restricted at higher velocities (Madsen et al., 2001). Roberts and Ludwig (1991) found a relationship between the zonation of emergent species and the strength of current and wave action and a gradual change in the plant community along the velocity gradient.

Chemical and mechanical control methods are often deployed to prevent infestation of channels by macrophytes (Franklin et al., 2008). However, natural hydrodynamic controls can obviate the need for such interventions (Duan et al., 2002). Groeneveld and French (1995) found that colonisation of channels by *Scirpus acutus* (tule) could be prevented if flow events of sufficient water velocity and depth were delivered. They showed that sufficient bending stress induced by hydrodynamic drag on the macrophyte stem caused stem rupture – failure involving permanent deformation and loss of plant function. They quantified the depth-velocity envelope required to induce rupture, providing a means to estimate the flow required to provide hydrodynamic protection against encroachment by macrophytes. The macrophytes studied by Groenveld and French (1995) were of a relatively stiff emergent type, while those in the Li River are submerged *Valisneria* spp., which have very flexible stems. So, the relationship of Groenveld and French (1995) would not apply in the Li Jiang.

Riis and Biggs (2003) found that macrophyte abundance peaked in the velocity range 0.3 – 0.5 m/s. Chambers et al. (1991) suggested 1 m/s as an upper limit of velocity, above which macrophytes are few or absent. Rea et al. (2002) reported that the velocity limit of *Valisneria nana* was 0.9 m/s. These general velocity-macrophyte abundance relationships were adopted for the Li.River.

Geomorphological objectives #1 and #2 are concerned with removal of fine sediment from the surface of the stream bed. These objectives apply to pools and riffles, or wherever it is important for ecological reasons to maintain a bed surface clean of fines. Sediment-entrainment theories can be used to predict the mobilisation of unconsolidated surface deposits on the bed (silt- and sand-sized). These sediments might accumulate during long periods of low flow. It is normally assumed that fine particles will be flushed out when the threshold of motion for some percentage of the particles is reached. One method of predicting when particles will become entrained in the flow is based on the Hjulström curves, which relate particle size to mean velocity required for erosion, deposition and transportation (Gordon et al 2004 p.192). The critical velocity (in m/s) for initiation of sediment movement (for particles >1 mm diameter) is ,$V_c = 0.155\sqrt{d_{50}}$, where d_{50} is the median particle diameter in millimetres. The Hjulström curve also predicts the limits for erosion of fine sands down to clay size sediment, and these values can be read from the curve. The velocity near the bed (V_b) is predicted by ,$V_b = 0.7\,V$, where V V is the mean channel velocity (Gordon et al 2004, p. 193). The bed surface material will become unstable when $V_b > V_c$.

Estimates of the discharge required to initiate movement of fine surface accumulations in the Li Jiang were made based on the assumption that the material covered the size range coarse silt up to fine sand. This assumes that clay- and fine silt-sized material either remains in suspension or forms flocs of organic/mineral/biological material that are not finer than coarse silt. These materials are entrained at mean channel velocities greater than 0.4 m/s. This is a conservative estimate, as much of the surface material is flocs of organic/mineral/biological material that is lower in density than mineral material, so it would be more easily entrained than mineral material.

On the basis of the above considerations, three geomorphological objectives were proposed. The magnitudes of these objectives (expressed here in terms of hydraulic criteria) can be expressed as discharge (m^3/s) through reference to the hydraulic model of the river.

Table 5. Geomorphic objectives

ID	Objective	Function	Flow component	Hydraulic criteria	Mean annual frequency / duration	Inter-annual frequency	Timing
G1	Flush fine sediment from surface of bed†	Remove the fine surface sediment after the low flow period to maintain a clean surface and sub-surface for utilisation by benthic invertebrates and benthic fish	Low flow pulse	$V \geq 0.4 \frac{m}{s}$ ¶	1 per year / 1 day	Every year	Mar-Apr
G2	Control macrophyte expansion and growth of algal mats	Prevent channel contraction‡ and build up of organic matter	High flow pulse	$V \geq 0.9 \frac{m}{s}$ ¶	1 per year / 1 day	4 in 5 years	April - July
G3	Maintain diversity and dynamism of channel form (width, depth, bars, bank shape, etc); mobilise bed material¥	Maintain habitat structure and diversity	High flow pulse	$\tau_b \geq \tau_c$ β	1 per year / 1 day	4 in 5 years	April - July

‡ The required duration of macrophyte control pulses is not known. One day is suggested as a starting point for evaluation. The flow pulse also needs to cover a reasonable proportion of the bed width (suggest 80% of late-spring to early-summer baseflow wetted width).

¥ Seasonally-independent, but recommended for the natural high flow season to align with high flow-associated biological processes.

¶ V = velocity.

β τ_b τ_b = bed shear stress; τ_c τ_c = critical shear stress for particle mobilisation

5.2. Water quality

Water quality is linked to flow via a number of mechanisms, but in particular via dilution of nutrient and sediment concentrations and, during low flows, also oxygen concentrations and temperature. At a workshop with PRWRC and invited experts water quality was identified as an important issue for environmental flows management; specifically ensuring that water quality is maintained at Grade II standard of national standard *GB 3838-2002 Environmental Quality Standards for Surface Water*, and that oxygen concentrations remain sufficiently high to protect local fish populations. Given the time and information constraints in preparing the current report, it has not been possible to ascertain the specific flows required to meet these objectives as part of this project (Table 5), although reports from recent years suggest that dry season flow volumes have dropped below levels where water quality is compromised. The proposed increase in flows to meet navigational and other ecological objectives may well be sufficient to achieve the water quality goals. This could readily be confirmed by evaluating historical water quality data. A final point to make about achievement of water quality targets is that increasing river flows to reduce concentrations of nutrients and sediment from point or diffuse pollution sources does not reduce the material loads, which are the original source of the problem. Thus, while it may be attractive to use flow increases to help achieve such targets, implementing strategies to reduce inputs (loads) would be more appropriate in the long-term.

Table 6. Water quality objectives

ID	Objective	Relates to	Function	Flow component	Hydraulic criteria	Mean annual frequency / duration	Inter-annual frequency	Timing
WQ1	Maintain minimum 2 mg/L dissolved oxygen, particularly in deeper pools	DO	To support aquatic life	Low flow	TBD	TBD	TBD	TBD
WQ2	Maintain nutrient concentrations below threshold for Grade 2 standards	N, P	Drinking water	Low flow	TBD	TBD	TBD	TBD

TBD: to be determined by future studies.

5.3. Fish

5.3.1. Introduction

Following global trends (ref), China's substantial fish biodiversity (estimated to comprise approximately 1500 species) has undergone major declines in abundance and richness over the last few decades, primarily due to:

1. Infrastructure associated with hydro-power generation or water resource development
2. Over-exploitation of fisheries
3. Pollution of water
4. Introduced species

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

Decline in fish populations in the Li River has been attributed to hydrological changes that have occurred since construction of major reservoirs, and there have been notable declines the abundance of important fisheries species as well as the species richness in the Li River since the 1970s (PRWRPB 2010 Figure 11, Li et al. 2011). The main disturbance mechanism identified by the project team and a workshop involving invited local experts was the disruption of spawning of many species and/or the loss of habitat continuity (both longitudinal, and lateral to wetlands, which are important for both spawning and recruitment migrations). Similar effects have been documented for the Yangtze River, where significant reductions in fish stocks have been attributed to loss of continuity between riverine and associated wetland habitats (Xie and Chen 1999, Liu and Wang 2010).

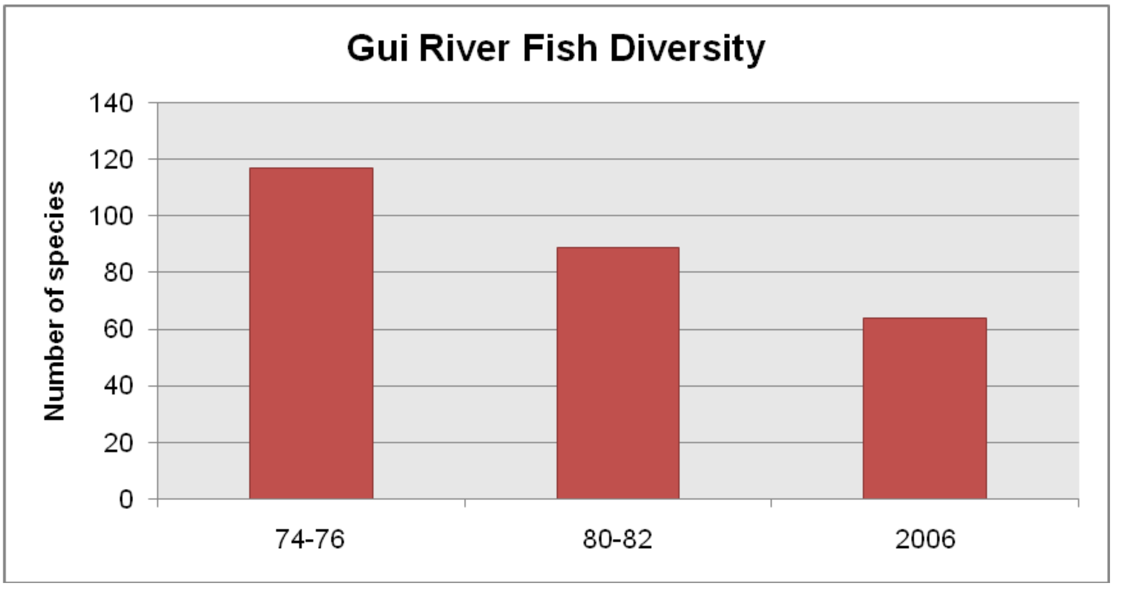


Figure 14. Documented declines in fish species richness in the Gui River since the 1970s

(Source PRWRC 2010).

Cease to flow events were not know to have occurred naturally in the Li River, and while there are no recorded instances of cease to flow in the recent gauging data, several recent droughts have led to very low flows occurring in the river. Coupled with high nutrient concentrations, which fuel respiration and oxygen demand, such conditions have a high potential to cause fish kills if they persist for long enough.

5.3.2. Life history strategies of fish in the Li River

Approximately 120 species of fish have historically been recorded from the Li River, however more recent surveys suggest the number of extant species is now closer to 70 (Figure 12). The sustainability of fish populations is considered a priority in terms of flow management, as well as environmental management and restoration more generally.

Consideration of the environmental flow requirements of fish requires an understanding of how different species of fish use the variety of habitats that are available to them. This concept extends to an understanding of why fish use particular habitats (e.g. foraging, spawning, growth) and also when fish require access to critical habitats. The historical fish community of the Li River included a range of life history strategies:

- Non-migratory freshwater dependent;
- Non-migratory estuarine dependent;
- Potadromous – freshwater migrations
- Anadromous – adults migrate from marine to freshwater habitats for spawning
- Catadromous – adults migrate downstream to marine habitats for spawning

Non-migratory freshwater and estuarine dependent species are permanent freshwater or estuarine residents. While they will undertake home range movements in search of food and habitat, there is no requirement for long-distance spawning or recruitment migrations. Consideration of the environmental flow requirements of this group should focus on relationships between flow and the availability of suitable habitats, food and spawning conditions.

Potadromous species undertake movements, within freshwater habitats, for the purposes of spawning and/or recruitment. In the case of the Li River, these movements can occur within (upstream and downstream) the main river channel, or between the main river channel and river- associated wetlands. Consideration of the environmental flow requirements for this group should include identification of flow-related migration cues, longitudinal (upstream-downstream) and lateral (river-wetland) habitat connectivity to provide access to spawning sites, as well has the relationships between flow, habitat, food etc. described above.

Anadromous species migrate upstream from marine habitats to spawn in freshwater habitats. Spawning sites may be located either in the main channel or in river associated wetlands.

Catadromous species migrate downstream from freshwater habitats to spawn at sea. These species are dependent on both freshwater habitats, and to a lesser extent, on the estuarine and/or near-shore environment in order to complete their lifecycle. In additional to the environmental flow requirements already identified (above), relationships between freshwater discharge and tidal exchange and their influence on longitudinal salinity gradients are also important. The presence of instream barriers now means that most extant fish species are either non-migratory freshwater or potadromous species that undertake limited movements within freshwater habitats, and some migratory species (Figure 15) such as *Parabramis pekinensis* have not been recorded for several decades.

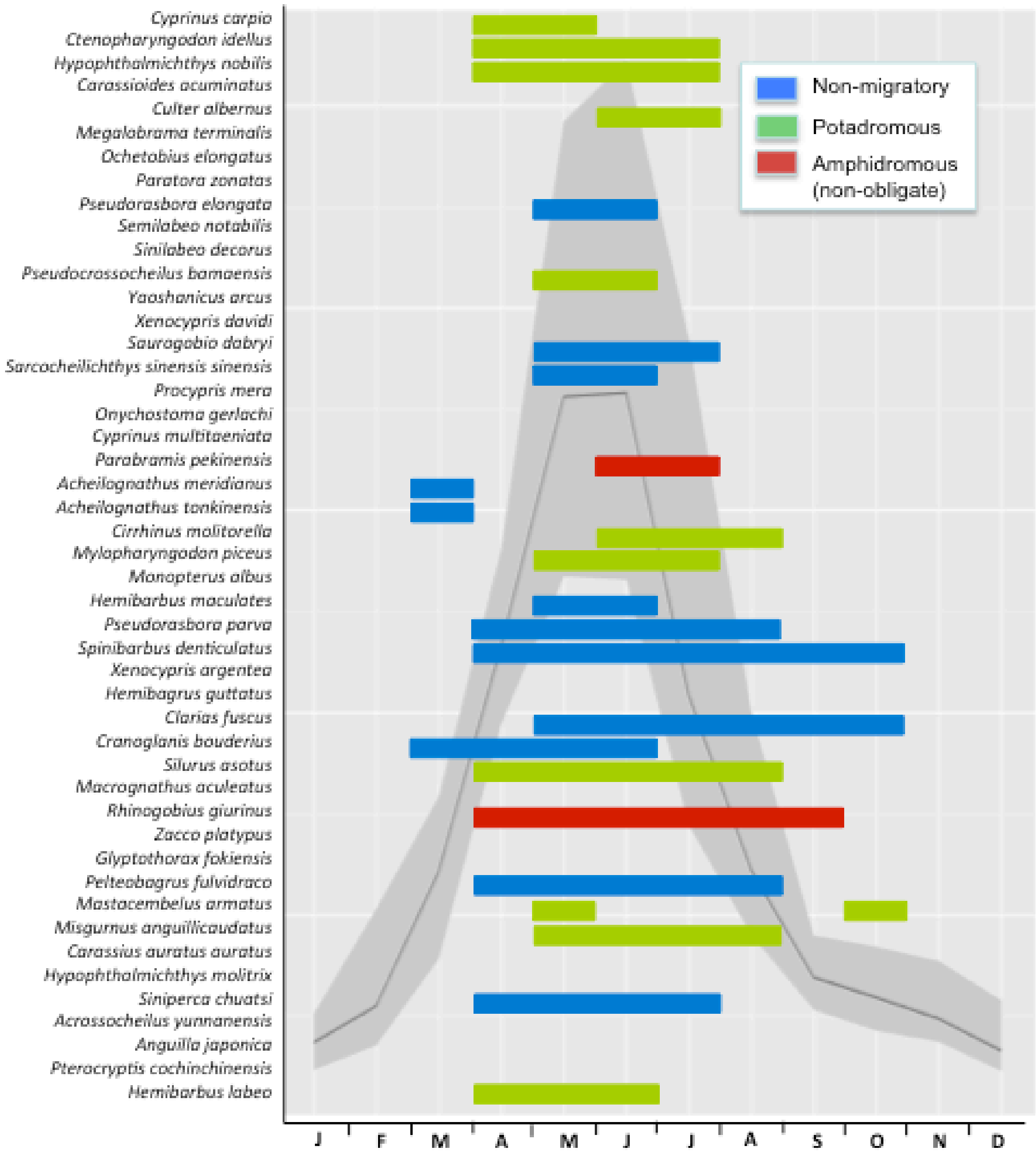


Figure 15. Plot showing the movement-requirements (colour code) and spawning timing (bar length) for fish species recorded in the Li River with available life-history data. The table is overlaid onto a plot of the monthly streamflows showing that spawning for most species coincides with the high flow (wet) season.

5.3.3. Flow dependent habitat requirements

In determining the environmental flow requirements of biota such as fish, it is important to incorporate both species that are of high value (whether for conservation, fisheries or tourism etc.), and also those that encompass the range of flow requirements of the full suite of species – the idea of focal species acting as an umbrella for those for which less information is available. Important species in the Li River include the 4 main Chinese carp species (black carp, silver carp, common carp and bighead carp) as well as other cyprinids such as *Spinibarbus denticulatus* (or, according to Li et al. (2010) *Spinibarbus hollandi*), numerous catfish (including armour and Amur catfish), and small bodied littoral species such as the loaches (*Misgurnus anguillicaudatus*). These species differ in their flow-habitat requirements, with some species more specific than others in terms of the flow conditions required for habitat and spawning. In particular, several of the Chinese carps are notable for their fairly specific spawning requirements. These biological requirements are summarized briefly below for several of the more common fish species.

Bighead carp (*Hypophthalmichthys nobilis*)

Bighead carp (*Hypophthalmichthys nobilis*) is a benthopelagic, potamodromous, freshwater species that lives in rivers with marked water level fluctuations, and overwinters in the middle and lower stretches. It is able to tolerate water temperatures of 0.5 – 38°C and high turbidity (FAO, 2011b).

Information on the biology and habitat preferences of bighead carp can be found in FishBase (Froese and Pauly, 2010). Bighead carp forages in shallow (0.5 – 1.5 m deep) and warm (> 24°C) backwaters, lakes and flooded areas with slow current; it is a bottom feeding fish. It undertakes long distance upriver migration at the start of a rapid flood and water-level increase (in April -July depending on locality, peak in May). Spawning grounds are usually located in river reaches characterized by turbulent or whirlpool-like flow, often in the vicinity of islands or stream junctions (Yih and Liang, 1964). Bighead carp breeds in very deep, very turbid and warm water > 18°C (usually 22 – 30°C), with high current (1.1 – 1.9 m/s) and high oxygen concentrations. It spawns in the upper level of the water column or even at the surface during floods. Spawning ceases if there is a fall in the water level, and then it resumes when water level increases. After spawning, adults migrate for foraging habitats. Semi-buoyant eggs are laid that are maintained in suspension by turbulence. The eggs are thought to die if they sink to the bottom. Larvae drift downstream and settle in floodplain lakes, shallow shores and backwaters with little or no current. During autumn and winter, when temperature drops to 10°C, juveniles and adults form separate large schools and migrate downstream to deeper places in main course of river to overwinter.

The key habitat and environmental flow requirements for bighead carp are:

- Diversity in channel morphology that creates large scale turbulent flow, such as associated with islands,
- Major bars, and tributary junctions (i.e. the tributaries are required to have significant inflow to the main river)
- Perennial flow to maintain suitable habitats
- Year round availability of hydraulic habitat for adult fish with low velocity and shallow depth 0.5 – 1.5 m.
- A rapidly rising and sustained flow pulse to stimulate spawning in April – July, with velocities of 1.1 – 1.9 m/s, depth > 2 m, and temperature > 18°C
- Following spawning, a flow of sufficient velocity (> 0.23 m/s) in the main river channel to maintain eggs in suspension

Grass carp (*Ctenopharyngodon idellus*)

Grass carp, *Ctenopharyngodon idellus*, is a demersal, potamodromous, freshwater species. It occurs in lakes, ponds, pools and backwaters of large rivers, preferring large, slowflowingslow flowing or standing water bodies with vegetation. Grass carp is tolerant of a wide range of temperatures from 0° to 38°C, salinities as high as 10 ppt, and oxygen levels as low as 0.5 ppm. This species prefers clear water but can tolerate high turbidity (Froese and Pauly, 2010).

Information on biology and habitat preferences of grass carp was collated by Stanley et al. (1978), Shireman and Smith (1983). Grass carp normally dwell in the mid-mid to lower-layer layer of the water column. Grass carp spawn in large rivers with well-vegetated, flooded lowlands; spawning grounds are usually located in river reaches characterized by turbulent or whirlpool-likelike flow, often in the vicinity of islands or stream junctions (Stanley et al. 1978). Flowing water and changes in water level are essential environmental stimuli for natural spawning; a rise in water level of >1.2 m within a 12-hour -hour period is thought to be required Bonner , although a rise in water level of as little as 0.10 – 0.15 m could be sufficient in some rivers (Shireman and Smith 1983). Movement for spawning begins in the period April – July (Jiang et al. 2010) when water temperature rises to 15 – 17°C; spawning begins at 18°C and peaks at 20 – 22°C (Stanley et al. 1978). Grass carp spawn on river beds with very strong current, in the range 0.7 – 1.8 m/s.

Semi-buoyant eggs drift 50 – 180 km before hatching (Shireman and Smith 1983 p. 12). Leslie et al. (1982) showed that eggs were adequately transported by a current of 0.23 m/s. The larvae hatch one day after spawning and make their way to vegetated lagoons impoundments or flooplain lakes. They begin feeding on rotifers at 2 to 4 days and change to larger zooplankton in about a week. Temperatures required for stimulation of sexual maturation, egg incubation, and survival of young range from 19 to 30°C, with an optimum of about 23°C. Because the requirements for each environmental factor must be found in juxtaposition, successful reproduction occurs in only a few locations (Stanley et al., 1978).

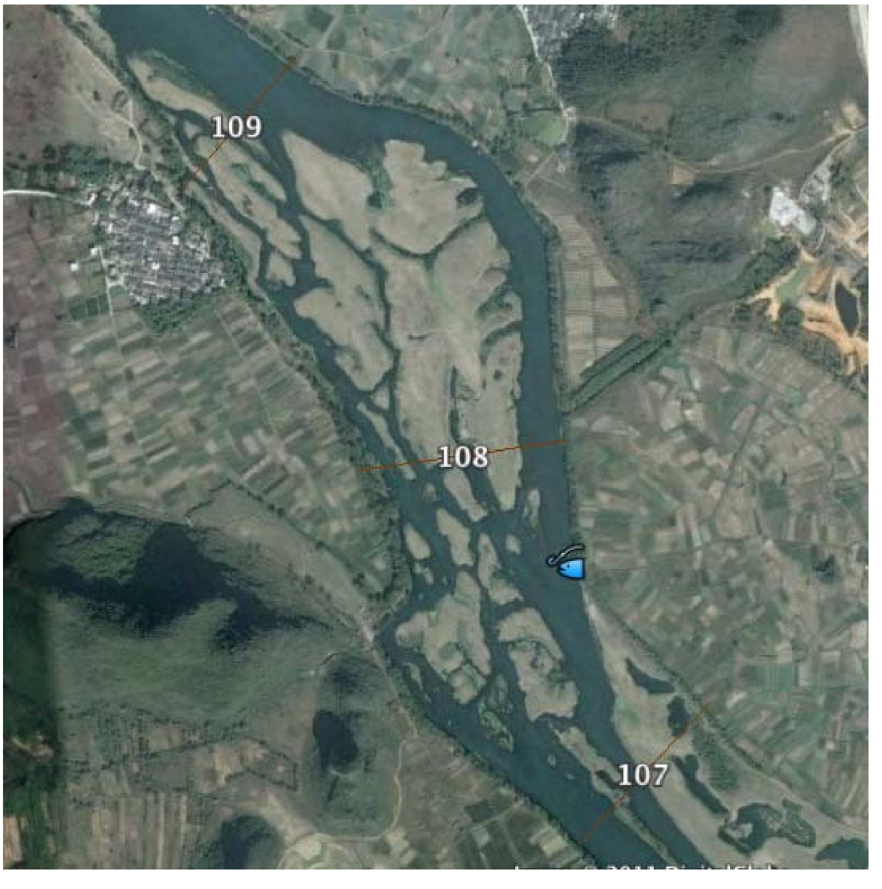


Figure 16. Example of a carp-spawning site in the Li River. The image is taken during low flows, but shows the complex floodplain architecture typical of spawning locations.

The key habitat and environmental flow requirements for grass carp are:

- Diversity in channel morphology that creates large scale turbulent flow, such as associated with islands, major bars, and tributary junctions (i.e. the tributaries are required to have significant inflow to the main river); also required are river associated backwaters and wetlands
- Perennial flow to maintain suitable habitats
- Year round availability of hydraulic habitat for adult fish with low velocity or standing water, and aquatic vegetation
- Seasonal connection between the river and associated wetlands for spawning and recruitment migrations
- A rapidly rising (>1.2 m within a 12hour12 hour period) and sustained flow pulse to stimulate spawning in April – July, with velocities of 0.7 – 1.8 m/s, and temperature > 18°C
- Following spawning, a flow of sufficient velocity (> 0.23 m/s) in the main river channel to

maintain eggs in suspension; temperature 19 to 30°C

Small bodied species e.g. Loaches (*Misgurnus anguillicaudatus* and *Cobitis sinensis*)

Although the Li River is inhabited by numerous small-bodied species, information on their flow and habitat requirements is limited. In general, these species are permanent residents of freshwater or estuarine habitats and prefer low velocity habitats, particularly in permanently inundated river associated wetlands and backwaters. Many of these species are omnivorous, including *M. anguillicaudatus*, which relies on macroinvertebrates, zooplankton, crustaceans and algae as primary food sources (Dulmaa 1999, Keller and Lake 2007), and moves into inundated backwaters and paddy fields during the wet season . Spawning generally occurs in spring and, depending on the species, eggs are either attached to either the substrate or scattered onto the streambed

The key environmental flow requirements for these species are:

- Habitat complexity, particularly the maintenance of low velocity backwaters and river associated wetlands
- Permanent, or regular, connection between the main channel and associated wetland/backwater habitats
- Maintenance of submerged, emergent vegetation as habitat and spawning sites
- Availability of substrates with fine particle sizes e.g. fine sands and muds
- Perennial flow to maintain suitable habitats

Catfish species (Bagridae), e.g. yellow catfish (*Pelteobagrus fulvidraco*) and Amur catfish (*P. ussuriensis*)

Several species of catfish (Bagridae), such as the yellow catfish (*Pelteobagrus fulvidraco*) and the Amur catfish (*Silurus asotus*) are known from the Li River catchment. Both are non-migratory freshwater species that inhabit both main channel and wetland habitats. Members of the Bagridae are generally benthic feeders. The yellow catfish is a good example, and feeds predominantly on aquatic insects (trichopterans and chironomids), molluscs, as well as cladocerans and zooplankton (Cao et al. 2009). Many catfish species are nest builders, in which they spawn and subsequently guard their eggs. Nests are often constructed from coarse particle sizes including sands and gravels and positioned in areas with some water flow so that eggs remain well aerated for the duration of development. Although limited information is available on the spawning requirements of catfish in the Li River,they are likely to have similar requirements for substrate and flow as described above, and are reported to spawn from April-August (peaking from May-July; Cao et al. 2009). It is thought that increases in both river flow and water temperature are important spawning cues.

The key environmental flow requirements for catfish are:

- Sufficient water velocities to maintain coarser substrates of sands and gravels required for nest building
- Increases in flow and water temperature for spawning cue
- Sufficient water velocities over nesting sites to aerate eggs

5.3.4. Fish flow objectives

A number of fish flow objectives were derived from consideration of the needs of key species representing the fish groups discussed above based on life history strategies. The objectives were specific to particular species and function, with each objective expressed in terms of hydraulic/hydrologic criteria and frequency/duration (Table 6). The application of these criteria is discussed in more detail in section 6.2.

Table 7. Fish-based flow objectives – relevant species, functions and criteria.

ID	Objective	Relevant species	Function	Flow component	Hydraulic criteria	Mean annual frequency / duration	Inter-annual frequency	Timing	Rise/ fall
F1	Maintain low flow habitat continuity through perennial flow	All species	Habitat maintenance	Low flow	Depth >0.2m	continuous		All year	-
F2	Maintain shallow habitats with moderate/high velocity for shallow water dwelling species, and spawners during low flow periods	Common carp, yellow catfish, weatherloach, goldfish	Resident habitat and/or spawning habitat	Low flow	Depth >1.5m Vel. < $1ms^{-1}$	Continuous		All year	-
F3	Maintain sufficient water depth in pools for large bodied fish	Big head carp, grass carp, Black carp, Chinese perch	Habitat maintenance	Low flow High flow	Depth >1.5m	Continuous		All year	-
F4	Stimulate spawning, migration (anadromy and potadromy) and maintain habitat continuity with spawning grounds and other sections of the river	Grass carp, big head carp, Amur catfish, armour head catfish	Spawning, spawning migration (upstream)	High flow pulse	Depth >2m, Vel. 1.1-$1.8ms^{-1}$	10-20 days	≥4 in 5 years	Apr-Jun	>1.2m in 12 hours
F5	Provide suitable habitats for spawning, and the development and recruitment of early life history stages by allowing access of large bodied fish to backwater and wetland habitats with abundant submerged vegetation	Grass carp, big head carp, Amur catfish, armour head catfish	Spawning, embryonic development and larval/ juvenile recruitment	High flow	Depth >0.2m in backwaters	continuous	≥4 in 5 years	Apr-Sep	-
F6	Maintain downstream transport of semi buoyant eggs within the water column	Big head carp, grass carp	Egg development and downstream transport	High flow	Channel velocity > $0.23ms^{-1}$	Continuous	≥4 in 5 years	Apr-Sep	-
F7	Maintain low velocity littoral habitats for small bodied species	Spined and Oriental wheather loach	Adult habitat	Low flow High flow	Depth > 0.2m Velocity <$0.5ms^{-1}$	Continuous		All year	-

5.4. Macroinvertebrates

5.4.1. Introduction

Macroinvertebrates are recognised as important components of riverine and wetland systems through their role in detrital processing (McQueen et al., 1986; Hall et al., 2003) and their contribution to food resources for a variety of fauna, including fish (Keast, 1985) and birds (Salgado et al., 2007). Macroinvertebrates are widely used as indicators of environmental change and for assessing ecosystem health of rivers due to the sensitivity of some taxa to a variety of disturbances including flow alteration and pollution.

5.4.2. Key flow dependence of macroinvertebrates

While less is generally known of the links between flow and the life-history of macroinvertebrates, flow reductions (both natural and anthropogenic) can have clear impacts on faunal composition, and this, together with their importance in food webs means that macroinvertebrates are frequently included in environmental flows assessments, but were not explicitly included in the present assessment due to the limited time available.

5.4.3. Aquatic macroinvertebrate flow objectives

No specific macroinvertebrate flow objectives were identified due to time limitations.

5.5. Vegetation

5.5.1. Types of riparian and riverine plants

Plant species that grow in and along rivers can be divided into three major categories based on their responses to flooding and drying. Terrestrial species inhabit the drier areas of the floodplain and river banks where the water table is below the soil surface or where soil is saturated. Amphibious species (semi-aquatic macrophytes) inhabit the wet-dry ecotone and require inundation at some stage in their life cycle. Submerged species (obligate aquatic macrophytes) conduct all of their life stages underwater. The response of plants to flood regimes determines the types of conditions that taxa can tolerate and their position in the river channel and floodplain (Table 7).

Table 8. Description of the three main categories used to group riverine plant species, and the habitats where species usually occur. Classification was devised by Brock and Casanova (1997) based on species' response to flood regimes in field and germination trials.

Category	Description	Typical habitat	Example species
Terrestrial	Species which germinate, grow and reproduce where is no surface water; can tolerate occasional flooding	Top of river banks, drier areas of floodplain, occasionally on islands in middle of channel	*Bambusa* spp., *Salix* spp.
Amphibious	Species which germinate in damp or flooded conditions, which tolerate variation in water level	Typically found in shallow water at edges of river channel, on instream bars and benches and in floodplain wetlands	*Alternanthera* spp., *Carex* spp.
Submerged	Species which germinate, grow and reproduce underwater.	Underwater to depths of 4-6 m depending on light penetration; can be fast-flowing to stationary water depending on species	*Vallisneria* spp., *Potamogeton* spp.

5.5.2. Vegetation flow requirements

Fluctuating water levels: riparian and riverine plants are adapted to fluctuating water levels. Regulation of rivers generally results in very stable water levels, except when water is released (or is no longer released) from a dam, which can result in abrupt and marked changes in water level. To maximise the functional diversity of species found along rivers (and to prevent dominance by a single type of plant), water levels should vary, ideally in response to local rainfall events. Water level fluctuations of 0.5-1 m every month for a period of 2-4 days should help to maintain a variety of plant species.

Variable flow velocity: as river water levels fluctuate with changes in discharge, flow velocity also changes. High habitat heterogeneity (variable physical form of the river channel and floodplain) means that a variety of flow conditions exist in a river system. Some aquatic plants are adapted to fast flows, whereas others can only grow in standing or very slow-moving water (i.e. lentic conditions). To prevent the dominance of aquatic plants that are adapted to lentic conditions (e.g. invasive *Eichhornia crassipes*, *Pistia stratioides*), flow velocity should vary in the main river channel (including areas upstream of dams). It should be high in the summer months (June-Aug) when most rainfall occurs, and can be lower in winter. Increasing flow velocities in summer is particularly important because aquatic plants undertake the majority of their growth and reproduction (i.e. spread) in the warmer months, and can become a nuisance at this time.

It is likely that temporally increasing water levels (above) and providing seasonal flooding (below) will meet the flow velocity targets; these strategies can be integrated and implemented together.

Seasonal flooding: many riparian and riverine plant species rely on floods to complete their life cycles: they may use flooding as a trigger for flowering or seed release, they may use them to disperse their propagules (seeds and vegetative fragments) and they may require them to provide suitable conditions for germination and growth (MERRITT and Wohl 2002, MERRITT et al. 2010).. Reflecting rainfall patterns, high flows historically occurred in the Li River in the summer months, typically peaking in June. Many of the plants that grow along the river flower and produce fruits at this time (Tables 3-5), and they would use the receding flood waters to disperse their seeds. As water levels drop in autumn and winter, riparian plant propagules would germinate on the moist soil and plants would have time to establish and grow before floods return the following summer. Many seeds are short-lived and must germinate immediately after dispersal, so it is important to provide the floods at the appropriate time (i.e. at the same time as seed release).

To provide suitable conditions for germination, water levels should peak in June-July for 3-6 days each year (WP_{100}). This will wet the soil and will help to transport seeds. Overbank flow that inundates the river banks and floodplain every 5 years for a period of 2 weeks will help to kill non-riparian plant species (including invasive ones, e.g. *Solidago canadensis*) and will facilitate recruitment of riparian trees on the floodplain.

Seasonal drawdown: water levels should be lowered in the river and floodplain wetlands once a year (WP_{60}), and almost complete drawdown should occur once in every 5-10 years (WP_{20}). Drawdown should occur at a time when rainfall is at its lowest and when the river would normally have low water levels (i.e. Dec - Jan), and should last for 2-4 weeks. Drawdown will help to control the abundance of nuisance submerged and free floating macrophytes, including invasive species (e.g. *Vallisneria spiralis*, *Eichhornia crassipes*).

Longitudinal and lateral connectivity: As well as altering flood regimes, dams, weirs, walls and fords can trap plant propagules (seeds and vegetative fragments) that are dispersed by water. Instead of seeds floating down a river or being transported onto a floodplain, they will be trapped in a reservoir or the main river channel, limiting plant dispersal and potentially altering plant community composition and reducing diversity (Jansson and Nilsson 2000, Jansson et al. 2000, 2005). Some fish species also disperse plant seeds, so structures that limit fish movement can also restrict movement of plant propagules(CHEN et al. 2009).. As well as the provision of environmental flows, the construction of fish ladders and small through-flow channels in dams and weirs are recommended. Occasional openings and channels should also be made in walls and levees to facilitate dispersal and recruitment of riparian plant species on the floodplain. It is also advisable to release water from the surface of dams (where seeds concentrate), rather than the bottom of the impoundment to facilitate the dispersal of plant propagules.

To facilitate a functionally diverse flora and healthy ecosystem, the flood regime and habitat requirements of the three groups of plant species should be considered. Different types of species are desirable because they all serve a different function. For example, riparian (terrestrial) trees help to stabilise the bank, they control the local environmental conditions of the riparian zone (Jiang et al. 2005) and can provide a source of fuel for humans. Amphibious plants that live on the edge of rivers and wetlands also play a role in bank stabilisation (which is especially important as water levels fluctuate) Xia, 2003, and can be a food source for humans. Submerged macrophytes help to inhibit algal blooms Floras, 2011. All of these plants provide habitat and food for animals, improve water quality and are valuable for tourism by providing a natural setting with nice aesthetics. We use the three plant categories to structure the flow objectives and requirements for riverine vegetation (Table 8), noting, however, that plants use many life history strategies, so these three categories can be divided further.

Table 9. Vegetation objectives

ID	Objective	Relevant species	Function	Flow component	Hydraulic criteria	Mean annual frequency / duration	Inter-annual frequency	Timing
V1	Maintain submerged aquatic vegetation	e.g. *Vallisneria*, *Potomageton* and *Myriophyllum* spp.	Plant diversity and Habitat structure	Low and high flow	>0.2m depth	Continuous		
V2	Maintain aquatic emergent vegetation, e.g. *Phragmites* and seasonally submerged meadow vegetation	*Phragmites* and seasonally submerged meadow vegetation	Plant diversity and Habitat structure	Low and high flow	Maintain sufficient wetted area	TBD	TBD	TBD
V3	Maintain seasonal flooding of in-channel floodplains and vegetated islands	Bambusa spp., Salix spp., Alternanthera spp., Carex spp.	Trigger flowering & seed release, disperse propagules (seeds and vegetative fragments), germination and growth	High flow pulse	>0.2m over in-channel island and floodplain	> 1 day	4 in 5 years	Mar-Aug

5.6. Tourism

Tourism is an important human use of the Li River with many boats navigating the river each day of the tourist season. During drought periods there is frequently insufficient water to allow boats to travel along the full section of river between Guilin and Yuangshou, and at times the river has become un-navigable. This is deemed unacceptable by authorities, and thus infrastructure changes are presently being made to allow an increase in minimum baseflows during the tourist season to 60 m^3/s. This minimum flow has arisen from modelling undertaken prior to this assessment to determine minimum depths for boat passage, and thus no hydraulic criteria have been explicitly stated. Nonetheless, it is expected that this flow would be set as a minimum flow in the river throughout the year, except during periods when critical human needs (i.e. drinking water/urban water demands) cannot be met (Table 9).

Table 10. Tourism objectives

ID	Objective	Relates to	Function	Flow component	Hydraulic criteria	Mean annual frequency / duration	Inter-annual frequency	Timing
T1	Maintain sufficient depth for navigation by tourist boats	Boat passage	Tourism, ecosystem services	Base flow	Minimum flows set at 60 m^3/s. See hydraulic tables for detailed depth/velocity information at this discharge.			
T2	Maintain sufficient wetted area to allow full reflection of scenery on the water surface	Aesthetics, tourist experience	Tourism, ecosystem services	Base flow				

Chapter 6. Hydraulic modelling

The previous section of the report outlined the environmental flow objectives and their rationale. This step brought together local expertise and input together with a comprehensive review of the scientific literature to try and establish the hydraulic and hydrologic influences of streamflow variability on physical, ecosystem and population processes. The next step is to link these requirements – often sourced from studies conducted in other rivers and expressed in units such as depth and velocity – to the local hydrologic conditions in the Li River. This step is undertaken using a hydraulic model of the study reach, which establishes how depths and velocities in the river channel vary with discharge. By running the hydraulic model at a range of discharge volumes, it is possible to build a fairly complete picture of how depths, velocities and wetted areas change as a function of discharge. This information can then be used together with the objectives tables, to define the river discharge required to meet each of the objectives in tables (Table 4-Table 9).

6.1. The hydraulic model

The hydraulic modelling was done using HECRAS, a 1-dimensional hydraulic modelling software tool developed by the US Army Corps of Engineers. Input to the hydraulic modelling encompassed the entire length of river between Guilin and Yangshou, with a total of 99 cross-sections (Figure 15), which ran from the top of the high bank on either side of the river, thereby encompassing the internal floodplain areas subjected to regular flooding. More details of the model parameterization process and settings can be obtained from PRWRC.

Figure 17. Short section of the Li River showing the spacing of cross-sections down the river.

6.2. Model outputs and use

HECRAS provides as output a suite of hydraulic variables for each cross section (Table 10), including maximum depth in the cross section, average velocity, wetted width, slope and shear stress. An important limitation with 1-dimensional models is that, with the exception of depth, most parameters are summarized as their cross-section averages, and thus maximum and minimum velocities may vary widely at any particular point in the cross-section from those reported by the model. Two approaches to dealing with this shortcoming are 1) undertake some field validation of the model results, to assess the extent to which the model outputs can be relied upon (this is good practice in any case), and 2) develop a two dimensional model of the reach, which provides information on vertically but not horizontally averaged parameter values in 2-dimensions within a reach (i.e. both across and up and down the channel [effectively a map view of each variable]). Software is also freely available to build such models but the data requirements are much greater and require different sampling approaches.

As already noted, the outputs from the HECRAS models are used in conjunction with the hydrologic summary information and the objectives tables to derive ‘flow rules’. To provide an example, fish objective F4 (provide suitable conditions for carp spawning and egg transport), requires depths >2m, and velocities between 1-1.8 ms^{-1} at spawning sites (Table 6). The HECRAS summary tables (Table 10) show that these requirements are each met by flows above 1000 m^3/s at most cross sections – at this discharge the median cross section velocity is 1.28 m/s, meaning that this target is met at more than 50% of cross sections. The target should also be examined specifically at cross sections coinciding with carp spawning areas. Examining the spells analysis results (Figure 9), it can be seen that these conditions (flows exceeding 1000 m^3/s) occur on average between 1 and 2 times per year in the wet season (the time when the recommendations apply), and typically last for just 1-2 days. Note that the recommendation arising from the objectives tables suggests these conditions should be met for 10-20 days. There is thus an inconsistency between the hydraulic model output and the characteristics of the historical spells, suggesting perhaps the 1000m^3/s estimate is too conservative. As a compromise, in the short-term, it is recommended to include the upper threshold spell (1-2 days @1000m^3/s) followed by the lower threshold spell (10 days@ 200 m^3/s), with appropriate rates of rise and fall. This would both achieve the flow thresholds identified in the objectives tables and be consistent with the historical flow regime. A similar analytical approach is applied to each of the flow rules (Table 4-Table 9) to derive the full suite of flow recommendations (Table 11). The table includes 3 separate estimates of the discharge required to meet each objective based on the range of variability of results at each of the 138 cross sections. The median estimate represents the flow volume (Q) that meets the objective at 50% of the cross sections, while the upper and lower bounds represent the flow required to achieve the objective at just one, or all of the cross sections respectively. In many cases, the minimum flow examined (20 m^3/s) meets the low-flow objectives at all cross sections. It is prudent to carefully re-examine all of the flow recommendations against a low and high flow spells analysis to check whether the volumes determined from the hydraulic modelling analysis are within the bounds of natural variability, and where not, to consider any other risks from such flow extremes that may not have been identified. However, in the Li River, the baseflow requirements for tourist boat navigation (T1) of 60 m^3/s exceed the minimum flows associated with many of the habitat objectives, and hence overcomes this concern (assuming 60 m^3/s is not in fact too high). Thus, the T1 objective is effectively the controlling objective in terms of meeting the overall low flow requirements, and hence is the major determinant of low flow water needs and reservoir management strategies.

6.3. Additional steps

At this stage, a number of flow volumes are still listed as ‘to be determined’ (TBD) in Table 11, as not all of the necessary information is currently available to complete the table, in particular in relation to several of the vegetation objectives and the water quality objectives. For floodplain and wetland vegetation requiring inundation of parts of the channel that are above the typical water level (V3), it is necessary to look at a number of appropriate cross sections (i.e. those containing in-channel floodplains) and determine the flow volumes that will inundate in-channel benches and floodplain areas. The flow that achieves this criterion is then set as the appropriate flow volume. Similarly, for emergent or seasonally inundated vegetation growing in shallow backwaters, it is necessary to look at the shape of multiple cross sections from areas where such vegetation is found, and establish what flows would be required to inundate those areas. The same approach applies to flow component T2, which aims to ensure that a sufficient area of the riverbed is inundated during the tourist season to ensure that mountains surrounding the river are reflected in the water-surface. As can be seen in the final table of recommendations (Table 11), these flows are yet to be established through additional analysis of the hydraulic model, and possibly additional field surveys, noting particular areas where inundation (whether periodic or seasonally (e.g. in the case of T2)) is desirable.

Table 11. Summary of hydraulic characteristics of the Li River between Guilin and Yuangshou under a range of discharge volumes.

Discharge (Q) m3/s	statistic	W.S.Elev (m)	E.G. Slope (m/m)	Vel Chnl (m/s)	Flow Area (m2)	Hydr Radius (m)	Invert Slope	Shear Chan (N/m2)	Shear LOB (N/m2)	Shear ROB (N/m2)	Shear Total (N/m2)	max depth (m)
20	median	125.03	0.00	0.15	137.05	1.04	0.00	0.78	0.00	0.00	0.78	1.96
30	median	124.94	0.00	0.20	155.74	1.11	0.00	1.37	0.00	0.00	1.32	2.16
40	median	124.98	0.00	0.23	175.76	1.19	0.00	1.67	0.00	0.00	1.67	2.31
60	median	125.07	0.00	0.29	208.86	1.38	0.00	2.36	0.00	0.00	2.35	2.52
80	median	125.14	0.00	0.33	247.34	1.47	0.00	3.04	0.00	0.00	2.87	2.74
100	median	125.24	0.00	0.37	276.13	1.52	0.00	3.58	0.00	0.00	3.39	2.92
200	median	125.62	0.00	0.52	402.57	2.01	0.00	5.75	0.00	0.00	5.38	3.51
300	median	125.93	0.00	0.61	506.20	2.38	0.00	7.32	0.00	0.00	7.30	4.02
400	median	126.20	0.00	0.69	595.58	2.69	0.00	8.84	0.00	0.00	8.84	4.51
1000	median	127.76	0.00	1.28	818.35	3.52	0.00	14.56	0.95	0.00	13.86	5.44
2000	median	129.26	0.00	1.81	1185.57	4.59	0.00	19.25	2.61	0.00	18.47	6.89

Discharge (Q) m3/s	statistic	W.S.Elev (m)	E.G. Slope (m/m)	Vel Chnl (m/s)	Flow Area (m2)	Hydr Radius (m)	Invert Slope	Shear Chan (N/m2)	Shear LOB (N/m2)	Shear ROB (N/m2)	Shear Total (N/m2)	max depth (m)
20	min	103.20	0.00	0.02	17.23	0.24	-0.02	0.00	0.00	0.00	0.00	0.23
30	min	103.35	0.00	0.03	22.62	0.29	-0.02	0.00	0.00	0.00	0.00	0.33
40	min	103.45	0.00	0.04	28.66	0.34	-0.02	0.01	0.00	0.00	0.01	0.44
60	min	103.60	0.00	0.06	39.20	0.39	-0.02	0.01	0.00	0.00	0.01	0.64
80	min	103.72	0.00	0.08	49.29	0.39	-0.02	0.02	0.00	0.00	0.02	0.81
100	min	103.83	0.00	0.09	59.42	0.45	-0.02	0.03	0.00	0.00	0.03	0.93
200	min	104.28	0.00	0.18	109.43	0.53	-0.02	0.09	0.00	0.00	0.09	1.27
300	min	104.61	0.00	0.24	146.61	0.72	-0.02	0.19	0.00	0.00	0.18	1.46
400	min	104.89	0.00	0.29	184.15	0.84	-0.02	0.32	0.00	0.00	0.29	1.68

Discharge (Q) m3/s	statistic	W.S.Elev (m)	E.G. Slope (m/m)	Vel Chnl (m/s)	Flow Area (m2)	Hydr Radius (m)	Invert Slope	Shear Chan (N/m2)	Shear LOB (N/m2)	Shear ROB (N/m2)	Shear Total (N/m2)	max depth (m)
1000	min	106.06	0.00	0.59	399.24	1.49	-0.02	2.63	0.00	0.00	2.63	2.95
2000	min	107.59	0.00	0.84	595.95	2.08	-0.02	3.96	0.00	0.00	3.96	4.07

Discharge (Q) m3/s	statistic	W.S.Elev (m)	E.G. Slope (m/m)	Vel Chnl (m/s)	Flow Area (m2)	Hydr Radius (m)	Invert Slope	Shear Chan (N/m2)	Shear LOB (N/m2)	Shear ROB (N/m2)	Shear Total (N/m2)	max depth (m)
20	max	146.46	0.01	1.16	975.18	7.33	0.02	18.78	4.47	0.52	18.78	13.33
30	max	146.57	0.01	1.33	991.50	7.37	0.02	21.94	6.50	1.47	21.94	13.51
40	max	146.67	0.00	1.40	1007.14	7.44	0.02	22.56	7.46	4.36	22.56	13.66
60	max	146.79	0.01	1.53	1031.73	7.56	0.02	25.69	9.54	8.02	25.69	13.87
80	max	146.93	0.00	1.62	1053.01	7.67	0.02	28.05	10.00	8.59	28.05	14.04
100	max	147.04	0.01	1.68	1068.63	7.74	0.02	29.52	10.04	8.39	29.52	14.19
200	max	147.52	0.00	2.10	1132.82	8.05	0.02	27.58	10.58	9.91	27.58	14.70
300	max	147.92	0.00	2.50	1242.58	8.27	0.02	29.80	12.62	11.08	29.52	15.06
400	max	148.26	0.00	2.79	1399.83	8.54	0.02	41.56	15.99	12.36	40.36	15.34
1000	max	149.19	0.00	2.66	1698.12	9.65	0.02	61.47	21.48	27.16	48.95	17.18
2000	max	150.55	0.00	3.59	2369.73	11.14	0.02	78.70	27.68	33.78	65.16	18.25

Table 12. Key flow recommendations

ID	Objective	Flow component	Mean annual frequency / duration	Inter-annual frequency	Timing	rise/rate	flow volume required median	upper	lower
v1	Maintain submerged aquatic vegetation,	Low and high flow	Continuous				20	20	20
v2	Maintain aquatic emergent vegetation, e.g. *Phragmites* and seasonally submerged meadow vegetation	Low and high flow	continuous				TBD		
v3	Maintain seasonal flooding of in-channel floodplains and vegetated islands	High flow pulse	> 1 day	≥4 in 5 years	Mar-Aug	See Figure 10	TBD		
T1	Maintain sufficient depth for navigation by tourist boats	Low flow	continuous				60	60	60
F1	Maintain low flow habitat continuity through perennial flow	Low flow	continuous		All year	-	20	20	20
F2	Maintain shallow habitats with moderate/high velocity for shallow water dwelling species, and spawners during low flow periods	Low flow	Continuous		All year	-	20	20	20
F3	Maintain sufficient water depth in pools for large bodied fish	Low and High flow	Continuous		All year	-	20	20	20
F4	Stimulate spawning, migration (anadromy and potadromy) and maintain habitat continuity with spawning grounds and other sections of the river	High flow pulse	1-2 days followed by	Every year	apr-jun	See Figure 10	1000	1000	1000
			10-20 days		Apr-Jun	>1.2m in 12 hours	200	200	200
F5	Provide suitable habitats for spawning, and the development and recruitment of early life history stages by allowing access of large bodied fish to backwater and wetland habitats with abundant submerged vegetation	High flow	continuous	Every year	Apr-Sep	-	TBD		
F6	Maintain downstream transport of semi buoyant eggs within the water	High flow	Continuous	Every year	May-July	-	100	100	100

	column								
F7	Maintain low velocity littoral habitats for small bodied species	Low flow and High flow	Continuous		All year	-	20	400	20
WQ1	Maintain minimum 2 mg/L dissolved oxygen, particularly in deeper pools	Low flow					TBD		
WQ2	Maintain nutrient concentrations below threshold for Grade 2 standards	low flow					TBD		
G1	Flush fine sediment from surface of bed	Low flow pulse	1 per year /	Every year	Mar-Apr		100	750	20
G2	Control macrophyte expansion and growth of algal mats	High flow pulse	1 per year /	4 in 5 years	April - July		1000	2000	20
G3	Maintain diversity and dynamism of channel form (width, depth, bars, bank shape, etc); mobilise bed material	High flow pulse		4 in 5 years	April - July		2000	2000	1000

Chapter 7. Summary of recommendations

By following the steps in the scientific component of the framework outlined in Figure 1 and summarized at the beginning of this report we have provided a preliminary (and minimum) set of environmental flow components that need to be provided (either through protection or augmentation of existing flows) to have some prospect of achieving the environmental flow objectives set out for the Li River. This largely entails three flow components:

1) **Low flows**: enhancement of dry season base flows, to improve navigation, and prevent periods of poor water quality
2) **High flows**: the protection of existing wet season base flows, to maintain habitat necessary for fish reproduction, and
3) **Flow pulses**: the maintenance of dry and wet season flow pulses, to maintain riparian vegetation, to maintain habitat, and to support fish reproduction.

The detailed flow recommendations shown in Table 12 can be consolidated into a single set of required flows which will meet all the objectives. This consolidated list is shown below in Table 13.

Table 13. Summary of flow recommendations based on adopting the minimum discharge required to meet all of the flow objectives specified against each flow component.

Flow objective ID*	Flow component	Mean annual frequency / duration	Inter-annual frequency	Timing	rise/ rate	Flow volume required (m^3/sec) Med	Up	Low
T1, T2, F1, F2, F3, V1, V2, WQ 1, WQ2	Low flow	Continuous	Every year	Sep-Feb	-	60	60	60
G1	Low flow pulse	1 per year	Every year	Mar-Apr	See Figure 10	100	750	20
F5, F7	High flow	Continuous	Every year	Apr-Sep	-	60	400	20
F6	High flow	Continuous	Every year	May-July	-	100	100	100
F4, F6, V3, G2, G3	High flow pulse	1-2 days followed by	Every year	Apr-Jun	See Figure 10	2000	2000	1000
		10-20 days		Apr-Jun	>1.2m in 12 hours	200	200	200

It is also true, however, that the complexity of environmental flow recommendations are generally correlated with the level of knowledge and data that can be used to help identify the important flow-ecology relationships in any given river system. The current recommendations are based on sound, but easily accessible information, and should undergo future refinement. They also have not been subjected to rigorous validation – either in terms of validating the hydraulic model or the flow-ecology linkages used to underpin the recommendations. They should therefore be treated as a demonstration of the process that can be applied to identify important flow components.

Additional work is required in particular to evaluate the effects of applying a one dimensional model to estimate depths and velocities at each cross section, and the extent to which discharge variation affects the amount of the channel that remains wetted – noting that the analysis here has focused largely on critical minimum and maximum depths and velocities, rather than the total area of the river meeting particular thresholds. Further consideration of rise and fall rates, and the influence of river flows on water quality and floodplain vegetation is also recommended. Finally, variability in river flows – whether among years, seasons or days – is an important natural characteristic of rivers. The recommendations from the current study focus primarily on identifying large and demonstrably important aspects of flow variation. Future work should focus on further evaluating these recommendations while at the same time considering other, potentially less obvious aspects of short-term flow variability. This will require local expert input from the disciplines of engineering, hydrology, fisheries management, floodplain and wetland ecology and water resource management, but broadly would follow a similar approach to that laid out in the current document.

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