PART 7: SUPPLEMENTARY PAPER – TAIZHOU ENVIRONMENTAL FLOWS REPORT AND RECOMMENDATIONS

Chapter 1: Introduction to Taizhou Pilot Project

1.1 Project context

The Water Entitlements and Trading ('WET') project is a joint initiative of the Australian Department of Environment and Water Resources ('DEW') and the Chinese Ministry of Water Resources ('MWR'), with funding provided by the Australian Agency for International Development ('AusAID'). The project aims to assist MWR in the development of a WET system suitable for implementation in China. The project aims to do so through reviewing current arrangements, and making policy recommendations, on seven components identified as critical to the establishment of a WET system. This report is primarily concerned with one of those components: environmental flow definition and management, although another of the components: water resources management modelling, is utilized as part of the environmental flow assessment process.

For each of the components, the WET project is undertaking research work and will make policy recommendations with a central government focus. This work is coupled with research in two pilot sites. One is the Jiao River (Jiaojiang) in Taizhou prefecture, in Zhejiang province. The other is the Hangjin irrigation district in Inner Mongolia autonomous region. The pilot sites are being used to inform the national-level recommendations, to test the practicality of the WET system being proposed, and to demonstrate its application. This report is concerned only with the Taizhou case study. A dam is proposed for Zhuxi, one of the headwater creeks of the Jiaojiang system, and there is a desire to establish a suitable environmental flow regime so that undesirable ecological impacts to the river are avoided.

The WET project adopts the philosophy that water is first divided amongst environmental and consumptive purposes; the water available for consumptive use is then shared amongst different users. The project is developing a decision-support tool to assist water resources managers in identifying key river assets, determining the flow requirements for those assets (i.e. what flows need to be provided for a healthy ecosystem), and modifying or implementing regulatory arrangements to provide for those flows.

In August 2007 the *Water Entitlements and Trading Project Phase 2 Mid-Project Report* (WET Project, 2007) provided background information on methods of environmental flow assessment, and suggested a framework for application to the WET project. In October 2007 an assessment was undertaken on the Zhuxi-Jiaojiang system. The review of information on the study area and the methodological details are reported elsewhere – the focus of this report is to document preliminary flow requirements to maintain and/or restore identified key ecological and environmental assets.

1.2 Pilot project objectives

Over the coming years, economic development and an increase in the standard of living are likely to combine to increase demand for water supplies in Taizhou. At the same time, Taizhou will need to ensure that its development is consistent with building a water saving society (WET Project, 2007). Taizhou receives relatively high and regular rainfall. These circumstances have meant that Taizhou has generally had more than enough water available to meet its consumptive needs. However, this culture has given rise to a number of water resource management issues (WET Project, 2007). One consequence of the assumption that there is an abundant supply of water is that little consideration has been given to environmental flow requirements. Over the long term, this is likely to pose risks to ecological health in the basin (WET Project, 2007). In this respect, Wet Project (2007) identified four main aspects of the problem:

i. Limited understanding of ecological needs for water. There is currently virtually no recognition of ecological needs for water in the basin.
ii. Management of resource availability. There is no mechanism to prevent total abstractions from exceeding the resource availability and, hence, becoming unsustainable and impacting on the natural environment
iii. Infrastructure design and operation. In designing infrastructure and determining operational rules, consideration is not given to environmental requirements.
iv. The impact of existing constraints need consideration. Extensive floodplain development will make it difficult to recreate previously occurring flood events because this would have major social and economic implications.

The Taizhou environmental flows pilot project aims to demonstrate how these issues can be addressed by undertaking a formal environmental flows assessment for Zhuxi downstream of the proposed reservoir (including the stream system down to the estuary). The main objectives of the environmental flows pilot project are to:

- Refine the suggested environmental flow assessment methodology described in Wet Project (2007) to suit the local physical and ecological conditions, data availability, resources available and time limitations;
- Demonstrate application of the refined methodology to the Zhuxi-Jiaojiang system by undertaking an environmental flow assessment;
- Produce a set of environmental flow recommendations for the Zhuxi-Jiaojiang system; and
- Transfer the technology through field demonstration, data analysis sessions, flow assessment workshops, and documentation (e.g. this report).

1.3 Purpose of this report

This report documents the work undertaken for the environmental flow assessment component of the Taizhou (Zhuxi-Jiaojiang system) pilot project. The environmental flow recommendations presented in this report should be regarded as preliminary, primarily because the limited timeframe over which the work was undertaken prevented full consideration of all of the issues. Future, more detailed, consideration of any aspect of the work described here can be used to refine the recommendations. Despite the preliminary nature of the recommendations, the methodology is regarded as appropriate for the situation.

The wide range of hydrological, geomorphological, ecological and water resource development conditions in China means that it is unlikely that a single environmental flows methodology will be universally applicable. This report is meant to provide a framework that can be used to guide future environmental flow assessments in China, but individual studies will still have to decide on which particular techniques (for data collection and analysis) are the most appropriate for the local conditions. To this end, this report provides a brief methodological review to assist practitioners in method selection.

Chapter 2: Methodology

2.1 Brief review of available methods

Tharme (2003) grouped environmental flow methodological types into four main categories, namely hydrological, hydraulic rating, habitat simulation (or rating), and holistic methodologies. Tharme (2003) also recognized two minor classes of methodologies: ‘combination’ (or hybrid) approaches which had characteristics of more than one of the four basic types, and a group termed ‘other’ which comprised techniques not specifically designed for environmental flow assessment, but which had been adapted, or which had potential, to be used for that purpose. Assessment of flood flows necessary for channel formation or maintenance is an important aspect of many environmental flow assessments. There exists a group of geomorphic techniques that are used for this purpose in association with some of the environmental flow methodologies. Brown and King (2003) classified environmental flow methodologies into two categories - prescriptive and interactive - from the perspective of their usefulness as a tool for negotiating trade-offs between stakeholders.

2.1.1 Hydrological methods

Hydrological methods are generally used only at the basin-wide planning level, or where resources do not permit a more detailed investigation. Most hydrological methodologies use simple rules based on flow duration or mean discharge to scale down the natural flow regime, while others accept flow reductions as long as flow variability is maintained within a certain range. Some hydrological methods lack a sound ecological basis, but most, at least in their original formulation, are at least partly based on observed or modelled flow-ecology and/or flow-geomorphology relationships. While numerous hydrological methods are described in the literature (Tharme, 2003; Gordon et al., 2004), only three are discussed here: Tennant method, Range of Variability / Indicators of Hydrological Alteration (RVA/IHA), and Ecological Limits Of Hydrologic Alteration (ELOHA).

Tennant Method

The Tennant method (Tennant, 1976) also referred to as the "Montana" method, is the most commonly applied hydrological methodology worldwide (Tharme, 2003), and it is in widespread use in China (Wang, 2006; Wang et al., 2007).

In the Tennant method, recommended minimum flows are based on percentages of the average annual flow, with different percentages for winter and summer months (Table 77). The recommended levels are based on Tennant's observations of how stream width, depth and velocity varied with discharge on 11 streams in Montana, Wyoming and Nebraska. At 10% of the average flow (the mean daily flow, averaged over all years of record), fish were crowded into the deeper pools, riffles were too shallow for larger fish to pass, and water temperature could become a limiting factor. A flow of 30% of the average flow was found to maintain satisfactory widths, depths and velocities. The choice of a maximum flow was based on the theory that prolonged large releases would result in severe bank erosion and degradation of the downstream aquatic environment. The method was designed for application to streams of all sizes, cold and warm water fish species, as well as for recreation, wildlife and other environmental resources.

Table 77: Critical minimum flows required for fish, wildlife, recreation in streams identified by Tennant (1976).

	% of mean annual flow	
Description of flows	**Dry season**	**Wet season**
Flushing or maximum	200% of the mean annual flow	
Optimum range	60 - 100% of the mean annual flow	
Outstanding	40%	60%
Excellent	30%	50%
Good	20%	40%
Fair or degrading	10%	30%
Poor or minimum	10%	10%
Severe degradation	0 - 10% of the mean annual flow	

One main limitation of Tennant's method is that application of the technique to other streams requires that they be morphologically similar to those for which the method was developed. The required criteria, however, are not given by Tennant, making direct transfer of the technique difficult. Field observation of the stream at the various base flow levels is recommended for verification. Also, as the method is based on the average flow it does not account for daily, seasonal or yearly flow variations.

Range of Variability / Indicators of Hydrological Alteration

The Indicators of Hydrologic Alteration (IHA) is a software program developed by The Nature Conservancy (http://www.nature.org/initiatives/freshwater/conservationtools/) that examines 33 IHA parameters (originally there were 32 parameters) and 34 Environmental Flow Component (EFC) parameters. The ecological relevance of the IHA statistics presumably (Table 78) derives from North American experience. While the ecological relevance of the IHA parameters are presented in a comprehensive fashion (Table 78), King County (2000) found that some of the parameters did not hold much ecological relevance for rivers in the northwestern USA. King County (2000) recommended that some of the parameters should be calculated using seasonal, rather than annual data. To our knowledge, the authors of the IHA have never published quantitative evidence of the link between the IHA parameters and the claimed “ecosystem influences”, and, to our knowledge, neither has anyone else. Smakhtin (2001) and Pyrce (2004) reviewed low flow indices used in the literature and did not report any such relationships. Thus, calculating IHA indices does not, on its own, constitute an environmental flows assessment, because (i) there is no quantitative link between the calculated flow and expected ecological response or level of environmental protection offered by the particular flow indices that are calculated, and (ii) having calculated the indices, the problem of how to build a flow regime recommendation still remains, i.e. how would these 33 numbers be used to instruct the operator of an existing or proposed dam to manage flow releases?

Table 78: IHA flow characteristics and their ecological relevance (North America). Taken from The Nature Conservancy (2007a).

IHA Parameter Group	Hydrologic Parameters
Ecosystem Influences	
Group 1: Magnitude of monthly water conditions	Mean value for each calendar month *12 Parameters*
• Habitat availability for aquatic organisms • Soil moisture availability for plants • Availability of water for terrestrial animals • Availability of food/cover for fur-bearing mammals • Reliability of water supplies for terrestrial animals • Access by predators to nesting sites • Influences water temperature, oxygen levels, photosynthesis in water column	
Group 2: Magnitude and duration of annual extreme water conditions	Annual maxima and minima: 1-, 3-, 7-, 30-, and 90-day means *12 Parameters*
• Balance of competitive, ruderal, and stress- tolerant organisms • Creation of sites for plant colonization • Structuring of aquatic ecosystems by abiotic vs. biotic factors • Structuring of river channel morphology and physical habitat conditions • Soil moisture stress in plants • Dehydration in animals • Anaerobic stress in plants • Volume of nutrient exchanges between rivers and floodplains • Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments • Distribution of plant communities in lakes, ponds, floodplains • Duration of high flows for waste disposal, aeration of spawning beds in channel sediments	
Group 3: Timing of annual extreme water conditions	Julian date of each annual 1-day maximum and each annual 1-day minimum *2 Parameters*
• Compatibility with life cycles of organisms • Predictability / avoidability of stress for organisms • Access to special habitats during reproduction or to avoid predation • Spawning cues for migratory fish • Evolution of life history strategies, behavioral mechanisms	
Group 4: Frequency and duration of high and low pulses	No. of high pulses each year; No. of low pulses each year; Mean duration of high pulses within each year; Mean duration of low pulses within each year *4 Parameters*
• Frequency and magnitude of soil moisture stress for plants • Frequency and duration of anaerobic stress for plants • Availability of floodplain habitats for aquatic organisms • Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses) • Nutrient and organic matter exchanges between river and floodplain Soil mineral availability • Access for waterbirds to feeding, resting, reproduction sites	
Group 5: Rate and frequency of water conditions change	Means of all positive differences between consecutive daily values; Means of all negative differences between consecutive daily values; No. of rises; No. of falls *3 Parameters*
• Drought stress on plants (falling levels) • Entrapment of organisms on islands, floodplains (rising levels) • Desiccation stress on low-mobility stream edge (varial zone) organisms	

The IHA parameters have been adapted for Taiwan (Table 79) by Herricks and Suen (2003). In developing an IHA for Taiwan, it was necessary to consider the timing and sequence of hydrologic events in the subtropical climate, so several parameters were calculated using seasonal data (resulting in a total of 65 parameters). In the Taiwan IHA the wet season is June to October. This includes the plum rain season beginning in late May to June and the typhoon season in summer. The dry season is November to May (Herricks and Suen, 2003). The claimed ecological influences of the IHA parameters for Taiwan were much less detailed than those claimed for North America.

Table 79: IHA flow characteristics and their ecological relevance (Taiwan). Taken from Herricks and Suen (2003). Wet season: from June to October, Dry season: from November to May.

IHA Parameter Group	**Hydrologic Parameters**
Ecosystem Influences	
Group 1: Magnitude of 10-day water conditions	Mean value for each 10 day period *36 Parameters*
• Availability of water • Availability of habitat	
Group 2: Magnitude and duration of annual extreme water conditions	Annual maxima and minima: 1-, 3-, 10-, 30-, and 90-day means *14 Parameters*
• Lateral connectivity • Habitat complexity • Patch disturbance • Colonizing ability • General mobility	
Group 3: Timing of annual extreme water conditions	Julian date of each dry season 1-day maximum and 1-day minimum, and wet season 1-day maximum *3 Parameters*
• Spawning	
Group 4: Frequency and duration of high and low pulses	No. of high pulses each season; No. of low pulses each season; Mean duration of high pulses within each year; Mean duration of low pulses within each year *6 Parameters*
• Spawning • Recruitment • Species richness • Length of life cycles • Age at maturity	
Group 5: Rate and frequency of water conditions change	Means of positive differences between consecutive daily values for wet season, and for dry season; Means of negative differences between consecutive daily values for wet season, and for dry season; No. of hydrologic reversals in dry season, and No. in wet season *6 Parameters*
• Length of breeding season • Spawning periodicity • Reproductive strategies • Drought stress	

In a refinement of the original IHA method, Richter, et al. (1997) introduced the Range of Variability Approach (RVA) in order to facilitate application of IHA to the problem of setting hydrologic restoration targets in managed river systems. Whereas the IHA identifies the degree of change in the indicators (from one period to another, or pre- and post-regulation), the RVA takes another step and develops ranges for natural variation of each characteristic. The method can be used to identify annual river management targets based on an allowable range of variation (e.g. ±1 standard deviation from the mean, or at the 16th and 84th percentiles) in each of 33 parameters. The method prescribes that environmental flow regime characteristics should lie within the targets for the same percentage of time as they did prior to regulation. This method has been applied in numerous environmental flow related studies (although mainly to examine the degree of flow alteration in already regulated systems) in North America and has attracted interest in a few other countries (Tharme, 2003). The IHA/RVA literature does not explicitly state how the IHA/RVA calculations are used to specify a practical flow regime that can be used to manage a river. River operators need specific instructions regarding magnitude, frequency, duration and timing for flow releases – arcane hydrological statistics are not implementable. This is especially the case for devising a flow regime for a proposed dam on an unregulated river (such as the Zhuxi case), because IHA and RVA both rely on comparing an impacted with an unimpacted time series.

The EFC is a suite of hydrologic flow parameters (part of the IHA software program), which represent an attempt to automatically identify and compute statistics on five flow components: low flows, extreme low flows, high flow pulses, small floods, and large floods (Richter and Thomas, 2007). This delineation of EFCs is based on the assumption that river hydrographs can be divided into a repeating set of hydrographic patterns that are ecologically relevant. According to The Nature Conservancy (2007a) the full spectrum of flow conditions represented by these five types of flow events must be maintained in order to sustain riverine ecological integrity. Richter et al. (2006) and The Nature Conservancy (2007a) provides a list of the hydrological parameters and associated ecological influences for the five flow component groups. Note that RVA analysis is only available for IHA parameters, and not for EFC parameters.

The IHA User's Manual (The Nature Conservancy, 2007a) provides no guidance as to how an analysis of EFC parameters can be used to make environmental flow recommendations (other than stating that the flow components must be maintained). While EFC analysis is useful for characterizing the flow regime, a separate process is required for shaping the environmental flow regime. For example, Richter and Thomas (2007) discuss several environmental flow case studies in which they have been involved, but make mention of IHA and EFC only in the context of using these tools to assess the degree of flow alteration as a preliminary step in the process.

Ecological Limits Of Hydrologic Alteration (ELOHA)

Apse et al. (2007) were of the opinion that none of the existing methods being applied in regional-scale water planning and allocation adequately address flow-ecology linkages in a manner that can be adapted for application globally across different regions and contexts. Also, Arthington et al. (2006) rightly took issue with a few recently recommended hydrological "rule of thumb" methods of setting limits on extractions on the basis that they lacked an empirical basis and did not consider the importance of flow variability. Arthington et al. (2006) and Apse et al. (2007) proposed an approach to the identification of environmental flow guidelines that bridges the gap between simple hydrological "rules of thumb" and more comprehensive (but expensive), river-specific, environmental, flow assessments. The approach is known as the Ecological Limits Of Hydrologic Alteration (ELOHA) and is described in The Nature Conservancy (2007b).

ELOHA is a general framework for developing scientifically-credible, environmental flow standards applicable at the multi-river (“regional”) scale, based on flow-ecology linkages, that can be applied anywhere in the world, across a range of data availability, scientific capacity and social/institutional context. This proposed framework is a consensus view of a wide range of scientists actively engaged in the area of environmental flows and hydroecology.

ELOHA utilizes both local and regional hydrologic and biological databases to generate robust flow-ecology response curves for different types of rivers. These flow-ecology functions correlate ecological risk, which cannot be managed directly, to streamflow conditions, which can be managed through water-use policies. Based on these flow-ecology relationships, regional environmental flow standards can be developed.

The Scientific Process of developing flow-ecology response curves involves four steps (The Nature Conservancy, 2007b):

- Step 1 is to compile a regional database of daily or monthly streamflow hydrographs representing both baseline (undeveloped) and developed conditions for “control points” (management points or sites of ecological data) throughout the region. Hydrologic modeling is used to extend the periods of streamflow data for gauged control points and to synthesize data for ungauged control points as needed.
- Step 2 is to classify river segments based on similarity of flow regimes, using hydrologic statistics computed from the baseline flow series developed in Step 1. The number of river types in a region ranges from one to as many as ten.
- Step 3 is to compute hydrologic alteration for each control point, expressed as the percentage deviation of developed-condition flows from baseline conditions at each control point, using six to ten flow variables that are strongly linked to ecological conditions and are amenable for use as water management targets.
- Step 4 is to develop flow-ecology response curves by associating percentages of hydrologic alteration with associated changes in ecological condition. A family of curves is developed for each river type, using a variety of flow and ecology variables.

The Social Process of using the flow-ecology response curves to manage environmental flows involves three steps (The Nature Conservancy, 2007b):

- Step 1 is to determine acceptable ecological conditions for each river segment or river type, according to societal values (i.e. it is accepted that the management target is not pristine condition).
- Step 2 is to develop environmental flow targets for each river segment or river type by using flow-ecology response curves to associate the desired ecological condition with the corresponding degree of flow alteration. The allowable degree of flow alteration is the environmental flow target.
- Step 3 is implementation of environmental flow management by incorporating environmental flow targets into the hydrologic model developed in Step 1 of the Scientific Process (above). As that model accounts for the cumulative effects of all water uses, it can be used to assess the practical limitations to, and

opportunities for, implementing environmental flow targets at any control point in the project area, or for every point simultaneously.

Discussion

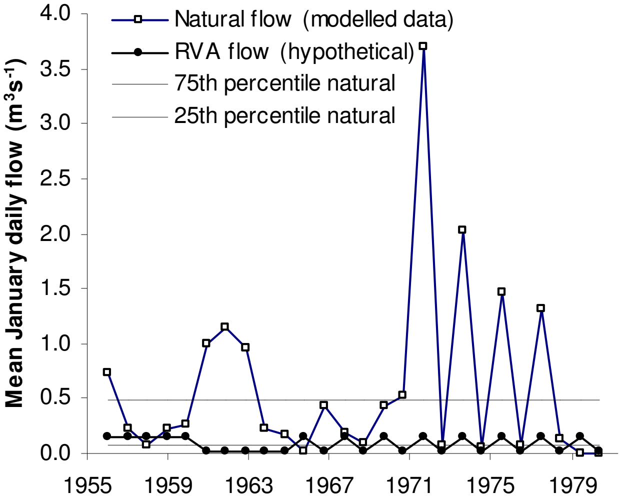
Orth and Leonard (1990), Dunbar et al. (1998) and Tharme (2003) concluded that simple hydrological methods requiring little or no field-work are most appropriate for basin-wide planning purposes, or for providing preliminary estimates in low controversy situations. A number of studies have compared hydrological methods with more sophisticated approaches (e.g. Orth and Maughan, 1981; Orth and Leonard, 1990; Caissie et al., 1998; Bureau of Reclamation, 1999). These comparisons were reviewed by Stewardson and Gippel (1997), who concluded that there was no consistent or reliable pattern in the relative magnitude of flows recommended by these methods.

The translucent dam principle (i.e. a percentage of the inflows are released downstream) aims to preserve temporal flow variability. While this may be desirable in some respects, the channel dimensions are not reduced, so the flows are under-sized with respect to hydraulics (i.e. tending to be shallower and lower velocity). This could mean that ecologically important depth and velocity thresholds are not achieved. Also, releasing water in this fashion (as opposed to targeted releases of certain flow components in their entirety) can have the effect of reducing mean dam levels (i.e. increasing airspace), leading to reduced probability of spills. This could have negative consequences for floodplain elements such as wetlands that rely on high flow events for inundation.

The RVA/IHA approach does not make specific recommendations for environmental flows. It is most often used to characterize the departure of regulated hydrological regimes from natural, rather than to build an environmental flow regime. However, it could be useful in demonstrating what components are missing from an existing regulated regime. Management of a regulated regime according to the range of variability would be difficult to implement, as calculation of the RVA statistics normally requires a time series of data (i.e. they can only be calculated retrospectively). However, it would be technically possible, if difficult, to manage river flows within the range of variability, so that at the end of each year the flows were compliant. This would be a particularly difficult task if the flow regime was required to be compliant with 33 parameters. It is worth noting that a conservative river manager could manage a river within the specified range of variability and still produce a river flow with relatively low variability compared to natural (Figure 71).

The empirical process of establishing flow-ecology response curves in ELOHA is similar to that used in some of the earlier “rule-of-thumb” methods. For example, the Tennant (1976) method was based on hydrological, hydraulic and ecological observations in 11 streams in Montana, Wyoming and Nebraska. The method was originally developed for application in that area, not worldwide. The difference with ELOHA is that the flow-ecology relationships are sought for smaller areas within regions (even though it may eventuate that a single set of relationships are adequate). Also, ELOHA seeks relationships for a number of ecological components, such as aquatic invertebrate species richness, riparian vegetation recruitment, or larval fish abundance (The Nature Conservancy, 2007b), while the earlier “rule of thumb” methods tended to have a more narrow focus on particular species’ of fish. However, it should be noted that Tennant considered aspects of water quality, channel stability and recreation needs in developing his flow-ecology relationships.

Figure 71. Natural (unregulated) mean January daily flow in the Fish River, NSW Australia (inter-annual C_v = 2.2), Range of Variability Approach (RVA) targets, and a hypothetical regulated flow regime that satisfies the RVA targets (inter-annual C_v = 0.9). Source: Gippel (2001).



Application of ELOHA would generally not be limited by the hydrological requirements of the method. Where adequate gauged streamflow records are unavailable, it is usually possible to model daily streamflows, although estimates of peak flows, low flows and cease to flow can be problematic in ungauged and poorly gauged catchments. Development of flow-ecology response relationships for streams within regions will potentially be time consuming and costly, although some regions will already have data available on which to base such relationships. Arthington et al. (2006) recognized that in establishing flow-ecology relationships, sophisticated sampling design will be required in order to separate the effects of flow modification per se from the effects of land use that often accompany major water resource developments (Bunn and Arthington, 2002).

One disadvantage of ELOHA is that it cannot be applied in regions where the streams are relatively un-impacted by flow regulation, because such areas lack opportunities to calibrate ecological response to existing gradients of flow alteration. In such circumstances, Arthington et al. (2006) recommended the use of methods such as DRIFT (Downstream Response to Imposed Flow Transformation) (King et al., 2003) that rely substantially on expert knowledge to describe and rank, from low to high, the probable ecological consequences of proposed hydrologic alterations.

One potential difficulty with ELOHA is that it appears to take no account of the geomophological and hydraulic dimensions of rivers. The method assumes that streams in a region with similar hydrological regimes will have similar ecological responses to flow. In many places, this may not hold, because streams within a region can have similar hydrology, but very different hydraulics, due to geomorphological variation. It cannot be assumed that the geomorphological characteristics of steams vary regionally with hydrological characteristics. The geomorphological variation of most interest would be degree of incision and aggradation, and sediment transport dynamics. For the same flow regime, the shear stress and sediment transport conditions in an incised channel are very different to those in an aggraded channel (Poff et al., 2006), and degree of floodplain connectivity would also be very different. These geomorphic/hydraulic differences would almost certainly give rise to different flow-ecology relationships.

2.1.2 Hydraulic rating methods

Hydraulic rating methods utilise a quantifiable relationship between the quantity and quality of an instream resource, such as fishery habitat, and discharge, to calculate flow recommendations (Gordon et al., 2004). Most emphasis has been placed on the passage, spawning, rearing and other flow-related maintenance requirements of individual, economically or recreationally important fish species. This approach is sometimes known as a 'transect method' or 'wetted perimeter method' because it involves measuring and interpolating changes in simple hydraulic variables, such as wetted perimeter or maximum depth, usually measured across single river cross-sections, as a surrogate for habitat factors known or assumed to be limiting to target biota. Commonly, shallow riffled reaches are chosen for analysis as these areas are the first to be affected by flow alterations, and because it is reasoned that maintenance of suitable riffles will also maintain suitable pool conditions. There is an implicit assumption in this method that there is a threshold value of the selected hydraulic parameter that if maintained in the regulated flow regime will maintain stream health (Gordon et al., 2004).

Simple wetted perimeter methods (Nelson, 1980) have been widely applied for many years (Tharme, 2003), and have been used relatively recently to make important environmental flow determinations (e.g. McCarthy, 2003). In the State of Washington, if fish habitat criteria are not available, then a wetted-perimeter method is used (Department of Ecology, 2003). When applied in its simplest form, transects are located in several representative riffles, and measurements of depth and velocity are taken over a range of different flows. A plot of wetted perimeter against discharge is drawn and the first break in slope in the curve is taken as an indication of the optimum, adequate or minimum discharge for the biota of interest.

As compared with hydrological methods, transect techniques take into consideration simple hydraulic requirements of biota and the availability of this habitat at various discharge levels. The need for field data makes the techniques more time-consuming and costly than hydrology-only methods. Hydraulic rating methodologies were the precursors of more sophisticated habitat rating or simulation methodologies, also referred to as microhabitat or habitat modelling methodologies (Tharme, 2003).

2.1.3 Habitat simulation methods

Habitat rating methods consider not only how physical habitat changes with stream flow (hydrology) but combine this information with the habitat preferences of a given species to determine the amount of habitat available over a range of stream flows. Results are normally in the form of a curve showing the relationship between available habitat area and stream discharge. From this curve, the optimum stream flows for a number of individual species can be ascertained and the results used as a guide for recommending environmental flows.

The most well known of the habitat rating methods is the Instream Flow Incremental Methodology (IFIM) (Bovee, 1982) and this method has been widely used throughout the world (Tharme, 2003). IFIM is much more than a habitat rating method. It is a problem-solving tool made up of a collection of analytical procedures and computer models. It was designed as a communication link between fishery biologists, hydrologists and hydraulic engineers. The aim of IFIM is normally to determine the effect of some activity such as irrigation withdrawals, dam construction or channel modification on aquatic habitat. As each riverine system will have different sets of flora, fauna, hydrological and hydraulic characteristics, types of disturbances and. regulating agencies, the IFIM allows the development of a different approach for each situation.

A number of alternative software systems with the same or similar components as PHABSIM have been developed for use with IFIM. These include EVHA, which is an adaptation of PHABSIM for use in French streams, RHABSIM, which is a commercial version of PHABSIM, and RYHABSIM, which is a New Zealand adaptation of PHABSIM with a simpler interface and fewer options (Gordon et al., 2004).

A critical limitation on the use of habitat simulation models is the lack of well-defined habitat-suitability curves. As these curves are essentially empirical correlations, the curves may not be transferable from one stream to another. However, the development of these curves is costly.

2.1.4 Holistic methods

Holistic approaches are essentially frameworks for organizing and using flow-related data and knowledge (Brown and King, 2003). This approach is not constrained by the analytical tools, and it is not unusual to make use of several different methodologies. While the hydrological, hydraulic rating and habitat rating methods usually focus on key sport fish such as salmonids, or fish with a very high conservation value, the holistic approach attempts to consider the entire ecosystem, using all available information, much of which may be little more than working hypotheses. The problem of uncertainty is overcome by adopting a conservative “precautionary principle”, and by recommending ongoing monitoring and adaptive management (e.g. Poff et al., 1997; Richter et al., 1997; Richter et al., 2006).

Holistic approaches cover a wide range of methodologies, including the Expert Panel Assessment Method, the River Babingley (Wissey) method, the Scientific Panel Assessment Method, the Building Block Method, the Holistic Approach, the Flow Restoration Methodology, the Benchmarking methodology and the DRIFT process (see Gordon et al., 2004 for references).

The holistic method is based on the natural hydrological regime and is intended to provide water required for the complete ecosystem including the river channel, riparian zone, floodplain, groundwater, wetlands and estuary. Explicit numerical models that relate discharge to aspects of the river’s hydraulics, geomorphology, water quality or ecology may be available, or even developed through the course of the investigation. Holistic methods typically build the environmental flow regime from key flow components that are known to be related to ecological processes. The magnitude of the flow components can be derived using a hydraulic model that relates water surface elevation, velocity, depth and/or shear stress to discharge, with field inspection relating these variables to important ecological components or processes. In the absence of hydraulic models, flow components can be defined on the basis of hydrological criteria alone, as is done in EFC (part of the IHA software program) (The Nature Conservancy, 2007a).

The Building Block Method builds the environmental flow regime from 3 main groups of flow components: low flows, channel and habitat maintenance flows, and spawning/migration freshes. The strength of the Building Block Method lies in its ability to incorporate any relevant knowledge, and to be used in both data-rich and data-poor situations (Brown and King, 2003).

The FLOWS method (SKM et al., 2002) is a derivative of the Building Block method, but it incorporates 7 season-specific flow components. This method uses a framework with a series of logical steps undertaken by a small team of experts in cooperation with the river manager: site paper; field inspection; issues paper (incorporating literature and data review and statement of flow objectives for ecology, geomorphology, water quality and hydrology); field topographic survey; hydraulic modelling; flows assessment workshop; flows recommendations paper. The recommendations are strongly linked to ecological and geomorphological objectives via the hydraulic models. The FLOWS method is the standard environmental flow method applied in Victoria, Australia.

The collaborative and adaptive method proposed by Richter et al. (2006) involves five steps: (1) an orientation meeting; (2) a literature review and summary of existing knowledge about flow-dependent biota and ecological processes of concern; (3) a workshop to develop ecological objectives and initial flow recommendations, and identify key information gaps; (4) implementation of the flow recommendations on a trial basis to test hypotheses and reduce uncertainties; and (5) monitoring system response and conducting further research as warranted. A range of recommended flows are developed for the low flows in each month, high flow pulses throughout the year, and floods with targeted inter-annual frequencies. Richter et al. (2006) presumably used an application similar to EFC to define flow components, but that study was based on only three of the five flow components identified by EFC: low flows, high flow pulses, and floods. The environmental flow method of Richter et al. (2006) involves much more than hydrological analysis. It also involves consideration of geomorphology and hydraulics (if available).

Like the FLOWS method, the collaborative and adaptive method proposed by Richter et al. (2006) also involves flow components, experts, managers and workshops. However, unlike the FLOWS method, the workshops involve up to 50 people, there is no survey and modelling step, and the 3-day post data review workshop process is expected to recommend environmental flows on the basis of existing information and expert knowledge alone (if hydraulic data are unavailable this is noted as a data gap). Richter et al. (2006) incorporate two post-recommendations steps: implementation and monitoring. An attractive aspect of this approach is that it accepts uncertainty in the recommendations and aims to refine them over time as knowledge of the managed system improves.

The benchmarking methodology undertakes basin-scale evaluation of the potential environmental impacts of future scenarios of water resource management (Arthington, 1998). In this method, flow alteration data and ecological impairment data are used to set two critical benchmarks (or risk levels); the first benchmark is the limit that must be placed on flow modification to achieve protection of the natural assets of the stream or river, whereas the second benchmark represents the degree of flow alteration associated with severely degraded river conditions. Benchmarking has become the standard method for setting limits to flow regime modification in rivers in Queensland, Australia.

The DRIFT methodology developed for use in southern Africa (King et al., 2003), evaluates links between flows and social consequences for subsistence users alongside ecological and geomorphological ones, and considers economic implications in terms of mitigation and compensation.

Holistic approaches share four main assumptions regarding achievement, or maintenance, of ecological integrity:

- some components of the natural flow regime cannot be scaled down, and must be retained in their entirety
- some components of the natural flow regime can be scaled-down
- some components of the natural flow regime can be omitted altogether
- variability of the regulated flow regime should mimic that of the natural flow regime, in certain respects

These assumptions arise from the notion that high- and low-flow events are more important than in-between conditions because of the stresses and opportunities they present to the biota (Poff et al., 1997). Also, many geomorphic and ecological processes show non-linear responses to flow, requiring a threshold to be exceeded before the process is activated (i.e. they cannot be scaled-down).

2.2 Brief review of methods used in China

In China, environmental flow requirements are variously termed “ecological water requirements/demand” or “environmental water requirements/demand” (Jiang, 2007), prompting Jiang et al. (2006) to adopt the general term “ecological and environmental water requirements” (EEWR). Environmental flows include water use not only for riverine ecosystems but also terrestrial ecosystems. Environmental flows may encompass water use for both for both natural and artificial ecosystems (Jiang, 2007). In general, there remains little use of theoretical models and quantitative methods for the assessment of EEWR in China (Jiang et al., 2006).

Most river EEWR studies are conducted in environmentally fragile areas, or in important basins in the northwestern and semi-arid regions, the Haihe Basin, the Luanhe River Basin and the Yellow River Basin. In general these studies have considered the requirements for sediment transport (generally related to bankfull flow), pollution dispersion, maintenance of aquatic life and prevention of excessive seawater intrusion into estuaries. A number of quantitative methods have been used to model the hydrodynamics and chemical balances of estuaries (Wang, 2007). Other studies have assessed the water requirements of groundwater systems and the needs of vegetation in arid and semi-arid regions, and lakes and wetlands, using water balance approaches (Jiang et al., 2006).

A recent study by Hou et al. (2007a, 2007b) assessed the impact of environmental flow releases made to the Tarim River in western China on water-table dynamics and vegetation, using a pristine reference site for comparison. This study found that in dryland areas, the underground water table is the most important and sensitive indicator of ecosystem response to environment flows. It is the constraining factor for riparian community restoration.

Wang (2006) reviewed the main calculation methods used to estimate environmental flow needs of rivers China. These methods are principally hydrological in nature and include the Tennant method (very widely applied), a monthly percentile method [monthly (yearly) guarantee rate], the method of assumption (which assumes that the average year will sustain the ecology, so this is the model for the environmental flow regime), and method of minimum flow in low flow season (the average discharge of the driest month over a ten year period as the ecological water requirement in low flow seasons). Wetted perimeter approaches have also been utilized.

Hydraulic methods are limited by the lack of detailed information on the hydraulic habitat needs of the biota, and the resources required for field survey appears to discourage this approach (Wang, 2006). The lack of information relating fish diversity to flow means that that diversity is replaced by biomass (the surrogate of which is available data on numbers of fish caught). In general, application of methods that relate biota to hydrology, hydraulics, and other requirements have been constrained by lack of ecological data, and the problem of pollution often being a dominant control on the distribution of biota (Wang, 2006).

2.3 Recommended methodology for Taizhou pilot study

In selecting an environmental flow methodology appropriate to the Taizhou pilot study, several factors need to be considered. The first group of factors concerns the local site factors, which relate to site complexity, resources available, practical constraints, and data availability (Table 80). When compared with the site limitations and requirements, each environmental flow methodology can be seen to have certain advantages and limitations (Table 81). Overall, it is apparent that holistic methodologies are the most appropriate for the Taizhou pilot study.

For this study it was decided to roughly follow the FLOWS framework. The Taizhou case study was essentially completed in only 2 weeks, while a FLOWS study would normally be undertaken over several months. This required substitution, modification or omission of certain tasks. The critical methodological steps were retained: determining the reaches (although site selection remained essentially ad hoc); reviewing the literature; making observations on the river; setting the flow objectives in terms of flow components; describing flow objectives using hydraulic criteria where possible; undertaking hydraulic analysis to link ecological and geomorphological processes to hydrology (although this was simplified); describing the current hydrological regime; defining the recommended flow components in terms of magnitude, frequency, duration an timing; and checking the compliance of the future (with dam) scenarios.

It should be noted that it will not always be possible or necessary in China to undertake an environmental flows assessment using the methodology described here. The method adopted for the Taizhou pilot study was deemed appropriate given the time and resources available. Also, it was considered desirable to demonstrate the advantages and limitations of including hydraulic analysis, i.e. going beyond a simple hydrological analysis approach.

2.4 Outline of methodological steps for the Taizhou pilot study

The environmental flows assessment was based on a combination of methodologies found in the literature, including hydraulic modelling. It is always preferable to include hydraulic assessment to support the hydrological analysis and ecological assumptions. Hydraulics, which is concerned with flow depth, velocity and shear stress, links ecology, geomorphology and hydrology by numerically defining habitats and ecological requirements. In this way, a particular objective, such as inundating a wetland, is defined in terms of one or more hydraulic criteria (in this case, a water elevation required to reach the sill), which can then be converted to a flow for specification as a requirement. Some processes cannot be readily defined in terms of hydraulic criteria, in which case expert knowledge is used to make recommendations based on knowledge of the natural hydrological pattern in the river.

Table 80: Taizhou pilot study relevant site factors for consideration of appropriate environmental flows methodology.

Factor for consideration	Relevant details for Taizhou pilot study	Implications
Time available	1 week allocated for field inspection; 1-2 week allocated for analysis and workshop	Relatively rapid field and analysis methods required
Resources available	Core team of fish biologist; hydrologist/geomorphologist; vegetation ecologist; 2 water resources modelers; 2 managers; 2 generalists; 3 translators (plus local field logistical support); no surveyor; no boat	Small team but high level of expertise available; relatively low cost field and analysis methods required; testing of scenarios possible
Importance of river assets	High rainfall zone; moderate ecological importance; good opportunity to recommend guidelines for operation of proposed dam; pilot study can demonstrate methods applicable to many other rivers	In some respects a high priority site deserving of high level of effort
Length and complexity of stream under consideration	Reaches from headwater (dam site) to estuary; complex issues (e.g. gravel extraction, diversions; groundwater interaction, angling, levees)	Requires flexible approach; a range of techniques likely to be required
Hydrological information availability	IQQM model of system available to report on current and future (with development) daily flow scenarios; limited stage height data from one gauge, modelled design flood peaks at dam site; virtually no knowledge of groundwater/surface water interactions	Not limited by availability of surface hydrology data; groundwater cannot be considered in any detail
Ecological information availability	Published literature from region and limited scientific surveys; local fisher survey; very limited vegetation data; limited habitat preference information and flow-ecology relationships	Reasonable knowledge of fish diversity; reasonable knowledge of key fish life cycles and habitat requirements; vegetation data to be collected in field
Geomorphological information availability	Good knowledge of estuary sediment dynamics; virtually no knowledge of stream geomorphology; no topographic or bathymetric data	Field survey required
Hydraulic information availability	Good knowledge of hydrodynamics of estuary, rating curve from one gauge; no hydraulic models of stream channel	Field survey required

Table 81: Appropriateness of a range of environmental flow methods to the Taizhou pilot study, given known site factors. See text for explanation of methods.

Method	Main limitations	Appropriate
Hydrological methods		
Range of methods used in China to date	Not well grounded in ecologic and geomorphic theory or local observations	No
Tennant	Derived in USA on the basis of site specific ecology and geomorphology; relevance of flow-ecology relationships to Chinese rivers questionable	No
RVA/IHA	Not designed for making specific environmental flow recommendations; relevance of IHA parameters to ecology of Chinese rivers questionable	No
EFC (IHA)	Not designed for making specific environmental flow recommendations; flow components appropriate but arbitrarily determined on the basis of hydrology rather than hydraulic-geomorphic-ecologic factors	No
ELOHA	Requires numerical flow-ecology relationships and regionalized hydrology – neither available	No
Hydraulic rating methods		
Wetted perimeter	Only appropriate for low flows; requires physical channel surveys	Maybe
Habitat simulation methods		
IFIM	Requires habitat preference relationships for key species – not available	No
Holistic methodologies		
Building Block method	Only uses 3 flow components; with expanded flow components the framework is appropriate	Partly
FLOWS	Normally requires channel surveys and 1-D hydraulic models which are beyond the resources of this project; with alternative hydraulic method the framework is appropriate	Partly
Collaborative and adaptive method	Only uses 3 flow components; requires large workshop groups and a high level of existing knowledge – not practical and data not available; adaptive management steps desirable	Partly
Benchmarking	Requires ecological condition and hydrological alteration data – neither available	No
DRIFT	Requires resources beyond the capacity of the project; the biophysical module may be appropriate	Partly

The main steps in the selected methodology for the Taizhou pilot study (Zhuxi-Jiaojiang system) were:

i. Divide the entire stream length of interest into manageable reaches, based on hydrological, geomorphological and ecological factors.

ii. For each Reach, identify valued ecological and environmental assets based on:

    a. existing reports, published and unpublished literature,

    b. field investigations, and

    c. discussions with project team members and interviews with water managers, fisheries officers and river users (e.g. fishermen).

iii. Use the same sources of information (existing reports, field investigations, interviews) to develop a conceptual model linking the identified assets to key aspects of the flow regime. The conceptual model provides a means of communicating important linkages between the identified ecological assets and specific flow related processes that must be maintained in order to protect those assets. These processes define the flow objectives.

iv. Having identified each of the important flow objectives for each Reach, use hydraulic and hydrologic models to determine the magnitude, duration, frequency and timing of flows required to meet these objectives. Note that due to practical limitations, Reaches 4, 5 and 6 were not hydraulically modelled, so flow recommendations were made using an alternative methodology. For these sites, a risk assessment was used to explore the likely consequences of flow alterations.

v. For each Reach, develop a set of specific flow rules for inclusion in a river operations model (in this case, IQQM). Note that these rules are designed to meet the objective of providing the minimum flow regime to sustain the ecological integrity of the river in the long-term at a low level of risk (i.e. it is not a "survival" flow regime that cannot be sustained in the long-term, nor is it an "ideal" flow regime, which is in fact the natural regime).

vi. Use IQQM to model the water resources availability with the dam in place and under the recommended environmental flows scenario. Based on need to meet security of supply objectives, review the environmental flow objectives to suggest alternative options. Each option will have associated risks. From a ecological perspective, assessment of the options should be based on the priority given to individual objectives outlined in the initial recommendations.

The final step 6 is not fully reported here.

2.5 Components of the flow regime

Although the flow in a river varies continuously from nothing up to major floods, most conceptual models exploring the influences of flow variation on river ecosystems identify key flow components (parts of the hydrograph) that serve important physical and biological functions [e.g. maintaining the channel morphology or sufficient minimum habitat during periods of low flow, as described in section 3.4 of Wet Project (2007)]. In this report, specific terminology has been adopted to describe each of the flow components (Table 82). Note that not all of these components are necessarily important or referred to in relation to in all reaches of the Zhuxi-Jiaojiang system, but they are noted here for potential application to other rivers in China.

The flow components were broadly associated with particular times of the year (Table 82), following the seasonal pattern of river flows (Figure 72). For the purposes of this study, the seasons were subdivided into four groups (Table 83).

Table 82: Description of flow components referred to in this report. EFC is Ecological Flow Components (Richter and Thomas, 2007).

Flow component	EFC equivalent	Hydrological description	Relevant season for Zhuxi-Jiaojiang
Cease-to-Flow	Closest is: 2. Extreme low flows	No discernible flow in the river, or no measurable flow recorded at a gauge.	Not characteristic of Zhuxi-Jiaojiang system
Low Flow	1. Monthly low flows	Provides a continuous flow through the channel during the low flow (dry) season, keeping in-stream habitats wet and pools full.	October – March
Low Flow Pulse	Closest is: 3. High flow pulses	Frequent, low magnitude, and short duration flow events that exceed the baseflow (Low Flow) for one to several days as a result of localised rainfall during the dry season.	October - March
High Baseflow	1. Monthly low flows	Persistent increase in baseflow that occurs with the onset of the wet season.	April - September
High Flow Pulse	3. High flow pulses	Increases in flow that exceed the baseflow (High Baseflow) as a result of sustained or heavy rainfall events in the wet season.	April - September
Bankfull Flow	4. Small floods	Completely fill the channel, some localized inundation, but no general spill onto the floodplain.	More common in wet season (April - September), esp. associated with typhoons (August – September)
Overbank Flow	5. Large floods	Higher and less frequent than bankfull flows, and spill out of the channel onto the floodplain.	More common in wet season (April - September), esp. associated with major typhoons (August – September)

Figure 72: Distribution of high flows, represented by 5th percentile daily discharge, in the Zhuxi-Jiaojiang system. IQQM modelled current scenario.

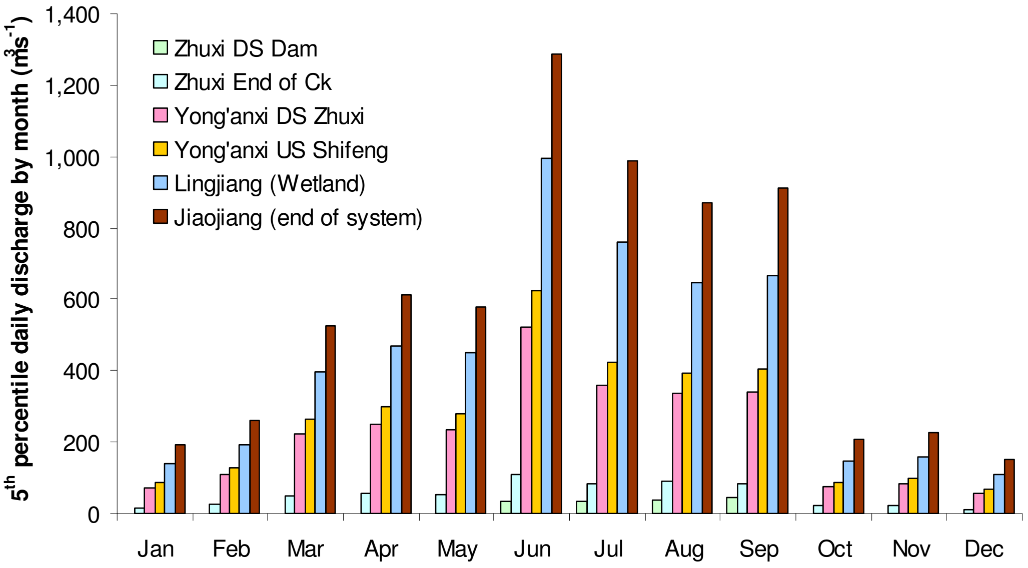


Table 83: Seasonality of flows in Zhuxi-Jiaojiang system

Month	Seasonal description
January	Autumn
February	Winter
March	Winter
April	Spring
May	Spring
June	Spring
July	Spring
August	Typhoon
September	Typhoon
October	Autumn
November	Autumn
December	Autumn

Chapter 3: Site and Reach Description

3.1 Mapping tools

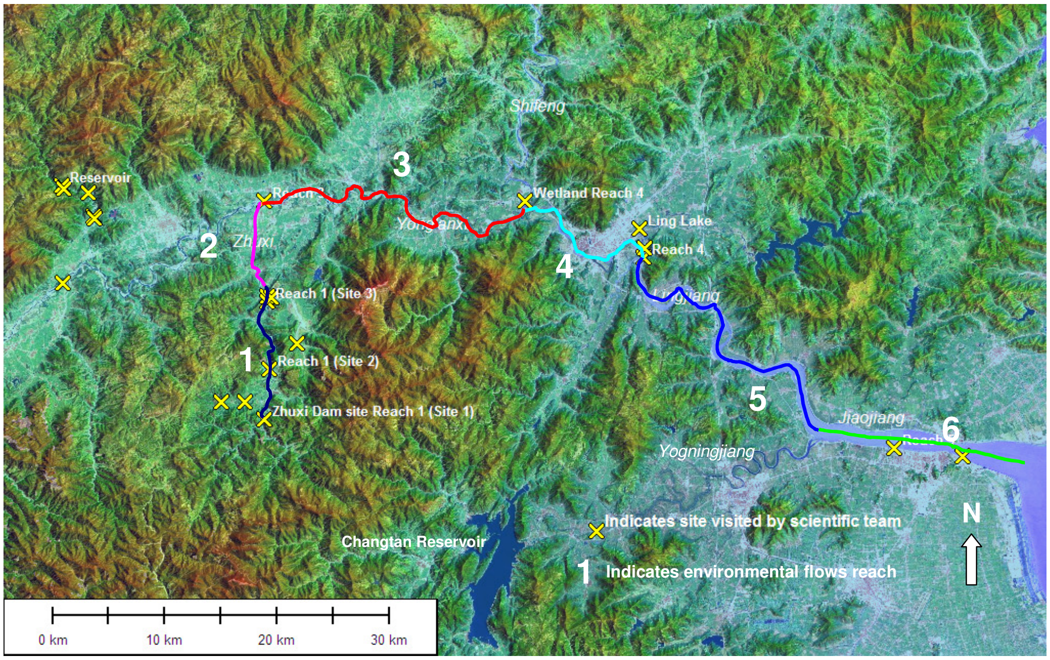
The environmental flows project required a topographic map of the catchment to assist with location of field sites, selection of reaches, estimation of stream gradient and geomorphological interpretation. Such a map was not immediately available to the project team, which may be a common situation in some parts of China. A digital georeferenced satellite image of the site area (as can be viewed on Google Earth) was downloaded for a cost of approximately US$90. The map was purchased from TerraServer® (http://www.terraserver.com/home.asp). Shuttle radar terrain model data were downloaded (free of charge) from NASA (ftp://e0srp01u.ecs.nasa.gov/srtm/). The Shuttle Radar Topography Mission (SRTM) obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth. SRTM consisted of a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000. SRTM is an international project spearheaded by the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). For China, data are available at 3 arc-seconds (90 metres) resolution. There are some issues with the accuracy of SRTM data as a DEM, particularly in forested and wooded areas, as the radar was reflected by dense vegetation. However, the SRTM is an adequate DEM when used at the catchment and sub-catchment scale.

The satellite image and SRTM data can be loaded by any GIS software; in this case Global Mapper (http://www.globalmapper.com/) was used to produce a composite map that allowed examination of the topography and main land use features (Figure 73). Global Mapper software can be purchased for a cost of approximately US$300.

3.2 Current basin water resources

Taizhou prefecture is located in the mid-coastal region of Zhejiang province. Taizhou has 21 rivers (including tributaries) each covering a basin area of over 100 km^2. The most significant is the Jiaojiang (Jiao River) (Figure 73). With a catchment area of 6,750 km^2 at the estuary (Zhang and Liu, 2002), the Jiaojiang basin is the third largest in Zhejiang province. Mean annual river discharge to the estuary is 211 m^{3}s^{-1} (Guan et al., 2005). The river transports a gravel/cobble bedload, and flows into an estuary characterized by inter-tidal mudflats.

Figure 73: Location of Zhuxi-Jiaojiang study area, showing 6 defined reaches for environmental flows assessment. Basemap is a composite of SRTM DEM and satellite image.



Taizhou receives regular and relatively high wet season rainfall due to monsoonal and typhoon influences. Average annual precipitation across Taizhou is 1,632 mm and average annual runoff ranges between 600 mm and 1,200 mm (WET Project, 2007)..

Floods are common in the wet season. However, a distinct dry season exists over winter. Periods of drought (or periods when rationing may be required) are of relatively short duration, as indicated by the current drought response arrangements that describe “extreme droughts” as those enduring more than 90 days (WET Project, 2007).

On average, about 9.08 billion m^3 of water resources is available annually. In 2005, about 1.54 billion m^3 was used throughout Taizhou (Taizhou Water Resources Bulletin, 2006, cited in WET Project, 2007).

Currently, there are four major storages in Taizhou (as described by WET Project, 2007):

i. The Changtan Reservoir (Figure 73) in Huangyan District is the biggest storage in Taizhou. It was built in the late 1950s – early 1960s on Yongningjiang. It has a capacity of 732 million m^3 and is used predominantly for urban supply to Jiaojiang township (the largest population centre in Taizhou). It also supplies water for the irrigation of about 66,667 ha (one million mu) of cultivated land. Dam releases are first directed through a hydropower station.

ii. The Niutoushan Reservoir in Linhai city was built in 1989 and is mainly used to supply two irrigation districts. About two-thirds of its 302 million m^3 capacity is used to irrigate almost 2100 ha (about 313,000 mu).

iii. The Lishimen Reservoir is on the upper reaches of the Shifengxi (which joins the Yong’anxi). It has a capacity of 199 million m^3 and is used for urban water supply (to the township of Tiantai), irrigation supply and hydropower generation.

iv. The Xia'an Reservoir is on the western boundary of Taizhou prefecture. It has a capacity of 135 million m^3.

There is also a large number of smaller storages throughout the prefecture, generally maintained by villages.

Groundwater resources are limited, generally very shallow and over-exploited. The extent of artesian groundwater development has caused serious land subsidence (Xue et al., 2005). Consequently, most artesian bores are being closed progressively (with only some to be retained for contingencies). Areas of restriction or prohibition have been established in the most overdeveloped sub-artesian groundwater areas. Groundwater resources are essentially reserved for low impact use such as stock and domestic (WET Project, 2007).

3.3 Proposed water resources development

Total water demand in the south of Taizhou (which is largely supplied by the Changtan Reservoir) is expected to increase from 76.5 million m^3 in 2010 to 117.7 million m^3 in 2020. Most of the additional demand will come from growth in urban and industrial consumption (WET Project, 2007).

A comprehensive water resources plan for Taizhou prefecture was finalised in 2004. This was prepared in accordance with central level and provincial requirements and in the context of water shortages that occurred throughout Taizhou in 2003 (WET Project, 2007).

A pipeline currently is being constructed to deliver water from the Changtan Reservoir to Yuhuan. It is due to be completed in 2009 and will relieve the water storage and distribution problems on the island, which required water shipments via tankers from Wenzhou prefecture in 2003 and again this year (WET Project, 2007).

Two major new dams have been proposed in the south-west of Taizhou to accommodate projected increases in water demand: the Zhuxi and Shisandu Reservoirs. The two new storages, when combined with the Changtan Reservoir, are expected to provide sufficient supplies (totalling 145 million m^3) for development in the south of Taizhou beyond 2020. A few other new storages are also proposed to be constructed in Taizhou by 2020 (WET Project, 2007). The Taizhou environmental flows pilot project is principally concerned with the Zhuxi Reservoir.

Zhuxi Reservoir is due to be operational by 2011. It will be located on Zhuxi (Zhu Creek) (Figure 73) in Xianju county. The construction of two or three new weirs on the tributary downstream of the dam is also proposed. The catchment area is 172.3 km^2 and the mean annual flow is 19 million m^3 (WET Project, 2007). The area to be inundated will be about 174 ha (2613 mu). The dam wall for Zhuxi Reservoir will be about 70 metres high. The storage capacity will be about 125 million m^3 and the effective storage volume will be 98.67 million m^3 (WET Project, 2007). The beneficial capacity (excluding the dead storage) is 93.53 million m^3. The dam will also have a flood mitigation function with a defence capability of 28.31 million m^3. The dam will increase the total annual volume of water supply by about 122 million m^3 (WET Project, 2007). The dam will also be used for opportunistic hydropower generation (that is, usually only when releases are made for other purposes) (WET Project, 2007).

There is a general expectation that urban and industrial users will receive an annual reliability of 95 or 97 per cent, while agricultural users will have 75 per cent reliability.

Designs for future water supply projects typically aim to achieve these reliabilities (WET Project, 2007).

3.4 Reach definition

The problem of environmental flow assessment and the issue of implementation of the agreed regime requires simplification of the river system into a manageable number of reasonably homogeneous reaches. The Jiaojiang study area was divided into 6 distinct river/estuary reaches (Figure 73, Table 84):

- Reach 1. Zhuxi (Zhu Creek) between the dam site and the first major downstream tributary entering Zhuxi.
- Reach 2. Zhuxi between the first major tributary below the dam site and the downstream confluence with Yong'anxi.
- Reach 3. Yong'anxi between the Zhuxi confluence and Shifengxi junction, the approximate upper limit of tidal influence.
- Reach 4. The freshwater estuarine section of Lingjiang (downstream of Shifengxi junction), which is under tidal influence but above the upper limit of saltwater intrusion from the sea.
- Reach 5. The estuarine section of Lingjiang (to Yogningjiang junction) that is influenced by both tidal and salinity fluctuations.
- Reach 6. The estuarine section of Jiaojiang (downstream of Yogningjiang junction to Taizhou Bay) that is influenced by both tidal and salinity fluctuations.

Table 84: Zhuxi and Jiaojiang system environmental flow assessment reaches

Reach number	Stream	Description	Stream type	Boundaries	Gradient (%)	Length (km)
1	Zhuxi	Directly downstream of dam	Freshwater, non-tidal	Dam to 1st major tributary (on right)	0.242	14.2
2	Zhuxi	Downstream of dam and tributary inflows	Freshwater, non-tidal	1st major tributary to Yong'anxi junction	0.242	9.3
3	Yong'anxi	Main stem fluvial	Freshwater, non-tidal	Zhuxi junction to Shifengxi junction (Sanjiangcun)	0.066	32.0
4	Lingjiang	Main stem fluvial	Freshwater (salt wedge limit downstream of Linhai), tidal at non-flood times	Shifengxi junction to tributary 15.1 km downstream	0.034	15.1
5	Lingjiang	Main stem estuary	Estuarine, tidal	31.5 km reach upstream of Yogningjiang junction	0.004	31.5
6	Jiaojiang	Main stem estuary	Estuarine, tidal	18.8 km downstream of junction to Taizhou Bay (Niutoujing)	0.000	18.8

Chapter 4: Identifying Environmental Assets

4.1 Asset identification

Information on ecological assets relevant to the flow recommendations was collected from background reports, literature surveys, field visits, discussions with Bureau of Water Resources and Fisheries Bureau staff, and interviews with local fishermen. In general, fish and fisheries emerged as the most highly valued asset, particularly those species of economic importance. Fish populations therefore form a core component of the environmental flows assessment. However, in recognition of the strong interdependencies between fish and other components of the riverine ecosystem, such as plants (aquatic and riparian), geomorphology, and water quality, these other factors were also considered for each reach. For example, flows to maintain fish must consider the effects of flow not just on fish directly (e.g. spawning cues), but also on flows to maintain habitat (e.g. geomorphology and macrophytes), food resources (e.g. invertebrates) and water quality (e.g. dissolved oxygen, nutrient loads etc.).

4.2 Geomorphology

4.2.1 Rivers and streams

Zhuxi is a cobble-coarse gravel bed river, with sand-sized material present within in the substrate. The bed material particle size was sampled at four sites using the Wolman Pebble Count method (Gordon et al., 2004, p. 105) (Figure 74). The creek bed is actively mined for sand and gravel in many places. In the lower reaches, downstream of Linhai city, the bed particle size changes to sand, and the estuarine section has a mud bed (Guan et al., 2005).

The morphology of the river varies throughout the study area. In overall size it increases from the dam site towards the sea. All along the system can be found long pools of variable depth (reportedly up to around 2 m at baseflow), separated by fast flowing runs and glides. There are occasional bedrock outcrops, especially noticeable in constricted sections. Large woody debris is not a feature of this river system.

The river appears to have a high sediment supply, which gives to a wandering gravel bed form. The bedload is shaped by high flows into large bars. Mounded gravel and cobbles form the banks in places, although most areas also have a fine grained (loamy sand and silt) floodplain present. The width of the floodplain varies enormously. In places the river is tightly constrained between valley walls, and in others it opens onto a floodplain that is kilometres wide. Much of the river is lined with artificial levees, offering protection for the floodplain land from floods of 20 – 50 year ARI. There was only one substantial floodplain wetland observed, on the left bank of the river just downstream of the Shifengxi junction (Figure 73).

Channel gradient varies from 0.24% for Zhuxi to virtually flat for the lower reach (Figure 75). There is a clear change in gradient just downstream of Linhai city, where the river is close to sea level. This is the natural limit of the upstream migration of the salt wedge from the estuary.

The relatively high channel gradient of Zhuxi and Yong’anxi, combined with ample supply of coarse bed material, meandering course and bedrock outcrops, generates a wide variety of hydraulic habitat. As well as fast flowing sections, there are deep pools, eddies and backwaters present.

Figure 74: Particle size of bed surface materials in Zhuxi (Reach 1) and Yong'anxi (Reach 3), determined by Wolman pebble count. It was not possible to sample the bed material at other reaches.

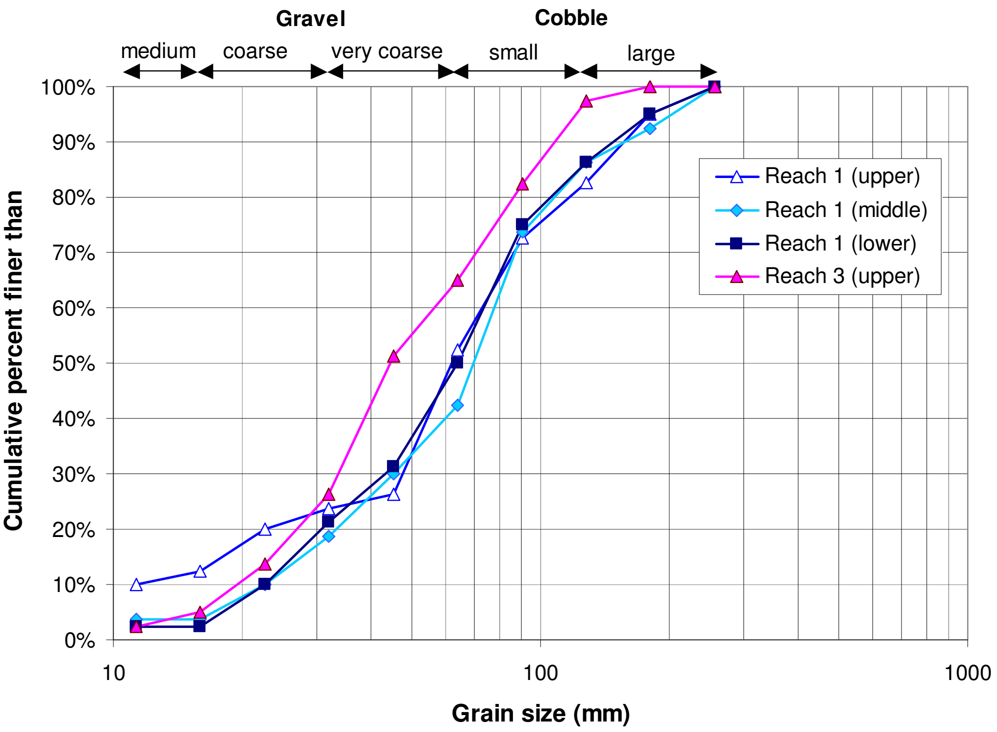
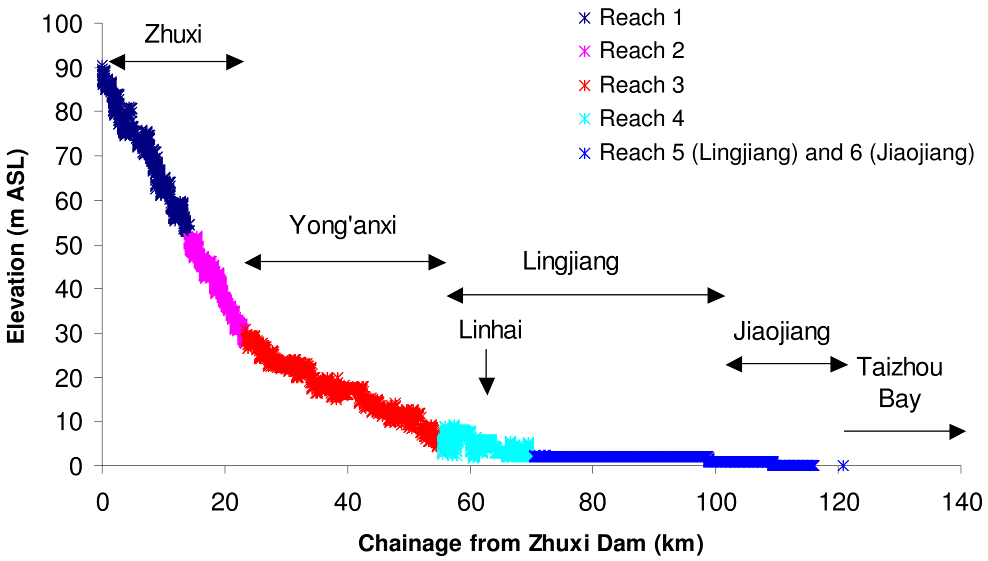


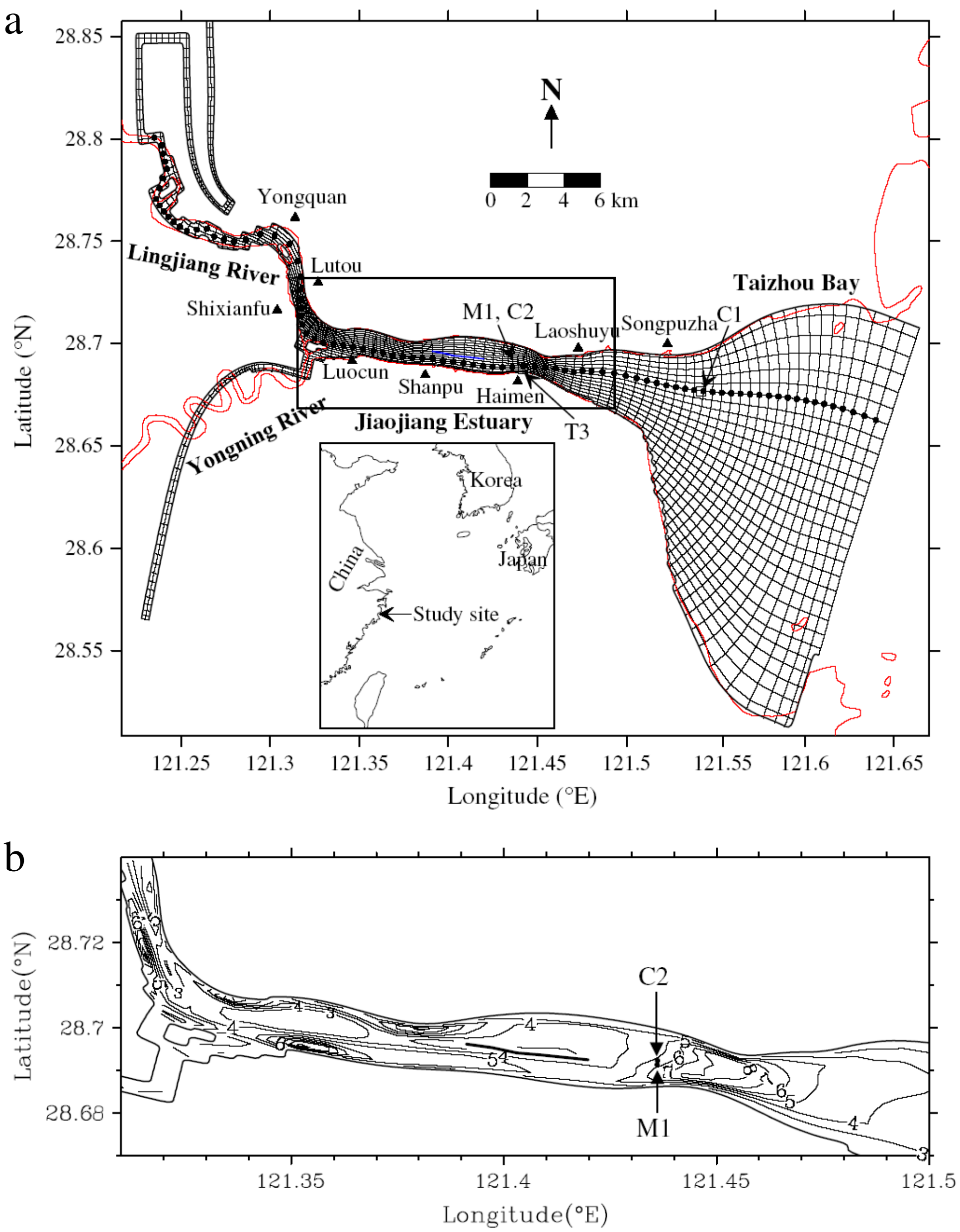
Figure 75. River profile for Zhuxi-Jiaojiang system determined from sampling the SRTM DEM.



4.2.2 Jiaojiang estuary

The water quality, sediment dynamics and hydrodynamics of the Jiaojiang estuary are well understood. According to Guan et al. (2005) the Jiaojiang Estuary is about 35 km long, although local knowledge suggests that saline water can reach almost as far as Linhai city. In the estuary, the mean width of the channel is about 1.2 km with a maximum of 1.8 km at the mouth (Figure 76). The estuary faces Taizhou Bay. The Jiaojiang River estuary was found by Guan et al. (1998) to be shallow with a depth of 1 – 3 m at low tide, although there are deeper sections of 6 – 8 m (Figure 76) (Guan et al., 2005).

Figure 76: (a) Orthogonal curvilinear grid used in the 3-D model simulations of Guan et al. (2005). M1 is the mooring stations; C1 and C2 are anchor stations; T3 is the tide station. (b) Bathymetry (in metres) for part of the estuary. Taken from Guan et al. (2005).



Semi-diurnal macro-tides prevail, with a mean tidal range of about 4 m and a maximum tidal range of 6.3 m. The vertically-averaged tidal current peaks at 2·0 ms^{-1}. At Haimen, the flood tide lasts 5.1 h while the ebb tide lasts 7.3 h (Dong et al., 1997). Off Haimen, the maximum flood and ebb currents are, respectively, 2.1 and 1.8 ms^{-1} (Zhu, 1986). The ratio of the freshwater volume to the tidal volume is about 0.04, but more than 0.1 during periods of very high river discharge. The estuary bed is covered everywhere with cohesive sediment (clay and fine silt with a diameter less than 8 μm). The estuarine waters are extremely turbid with suspended sediment concentration values at times exceeding 40 kg m^{-3} during spring tides in calm weather. The total mass of mobile sediment trapped in the estuary is around 1.2 x 10^6 tons, which is a value comparable to the annual river load (Guan et al., 2005).

In order to maintain a constant bed elevation, the Jiaojiang estuary is dredged at an annual rate of about 0.05 – 0.3 m per year (Guan et al., 1998). Guan et al. (2005) cited Bi and Sun (1984) and Fu and Bi (1989), who estimated that the average fluvial sediment inflow to Jiaojiang estuary is about 1.2 x 10^6 tons per year, corresponding to a mean sediment concentration of 0.18 g L^{-1}. Of the sediment deposited on the bed of the estuary, only 5% is due to locally derived fluvial material. The sediment infilling the estuary originates from the Changjiang (Yangtze River). The mouth of the Changjiang is located 200 km further north and the Changjiang sediment is known to travel long distances along the coast (Figure 77) (Liu et al., 2007). The Changjiang river plume is especially marked during the summer(Typhoon) season (Hung et al., 2007). .

The 3-D hydrodynamic model of Guan et al. (2005) (Figure 76) predicted that during a low river discharge, the total mass of suspended mass decreases, and this results in increased sedimentation. Saline water moves further upstream, and the vertically-averaged and time-mean values of suspended sediment concentration are reduced. During high river discharge, the sediment is gradually carried out of the estuary. The kinetic energy increases during ebb and decreases during flood. The masses of mobile sediment, stationary sediment, and total sediment are reduced, while turbidity maximum moves seaward to Taizhou Bay.

On a list of the 13 major coastal rivers in China (Figure 77) compiled by Zhang and Liu (2002), the Jiaojiang has the smallest catchment area (half the size of the second smallest), but was ranked 11th for discharge, 8th for sediment load, and 2nd for sediment yield (Figure 78). These data suggest that in terms of sediment yield, the Jiaojiang and the Huanghe (Yellow River) are in a class of their own (Figure 78). Given that the majority of the suspended solids in the Jiaojiang Estuary are sourced from coastal water transport (Figure 77) rather than riverine discharge, the river sediment load and yield data in Zhang and Liu (2002) are questionable. The value of fluvially derived sediment load to Liaojiang estuary reported in Guan et al. (2005) is more consistent with the yield data from the other major rivers in China (except the Huanghe) (Figure 78). This suggests that the Liaojiang catchment is not exceptional with respect to suspended sediment transport.

Figure 77. (a) Major coastal rivers in China, from Zhang and Liu (2002), and (b) schematic representation of various waters in the East China Sea from Hung et al. (2007). CJCW, Changjiang Coastal Water; KW, Kuroshio Water; TCWW, Taiwan Current Warm Water; UW, Upwelling Water; YSCW, Yellow Sea Cold Water.

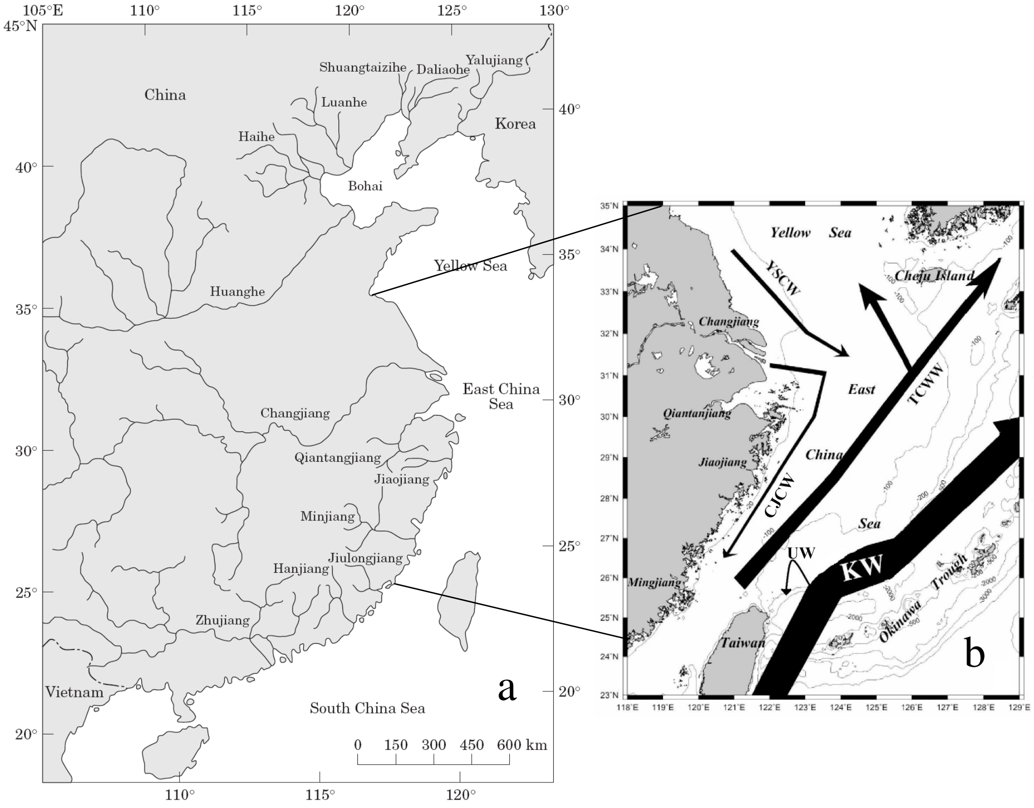
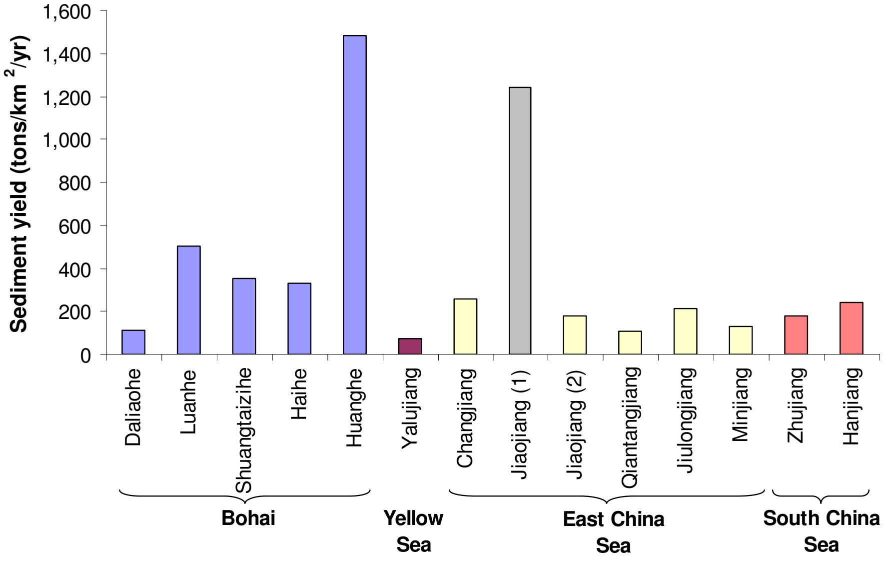


Figure 78. Average annual sediment yield for major Chinese rivers. Source: from data in Zhang and Liu (2002), except for Jiaojiang (2) which is reported in Guan et al. (2005). Jiaojiang (1) value is doubtful.



4.2.3 Flow-related geomorphic issues

In the fluvial reaches of the Zhuxi-Jiaojiang system it is important to maintain bed material disturbance (i.e. sediment transport) to maintain ecological processes. One component of this process is reasonably frequent flushing of fine deposits from the bed. The other major geomorphological issue is maintenance of channel form, with respect to the overall channel size, and the physical forms within the channel. Once again, this relates to maintenance of sediment transport processes.

Zhuxi Reservoir will trap the entire bedload at that point. Downstream of the dam the river channel will incise into the dominantly gravel and cobble-sized bed material to bedrock or until the remaining bed material is coarse enough to resist mobilization (to create an armoured bed). The results of this process were observed downstream of an existing reservoir flowing on a northern tributary of Yong'anxi (Figure 79). In this case the bed downstream of the dam was either bedrock or boulder-size. At a distance of around 1 km from the dam the bed material contained some finer material, and within 5 km downstream of the dam the bed material contained gravel and cobbles. Thus, in this case the incision recovered over a reasonably short distance downstream of the dam, indicating ample local sediment supply. There is little that can be done to prevent this scour process downstream of dams, short of ongoing augmentation of the sediment supply (Bunte, 2004). Merz and Ochikubo Chan (2005) found that cleaned gravels artificially sourced from adjacent floodplain materials were quickly incorporated into the stream ecosystem. Benthic macroinvertebrate assemblages on salmonid spawning enhancement materials, as indicated by species richness, diversity and evenness, were similar to those of adjacent un-enhanced spawning areas within 4 weeks of augmentation and supported higher benthic density and dry biomass for up to 22 weeks after placement. Bed material agumentation downstream of dams is an expensive and logistically difficult procedure and would only be warranted if it could be demonstrated that there would be no significant negative impacts and the gravel-dependent ecological, economic and social assets of the river were of sufficient value.

The bed load of channels of the Zhuxi-Jiaojiang system is sourced from inflowing tributaries, the channel bed itself and the channel banks. Ongoing construction of dams will reduce tributary sediment supply, and gravel extraction, which is prolific in the Zhuxi-Jiaojiang system, will reduce in-channel supplies. The expected response will be channel incision (sourcing material stored from the bed), followed by a phase of channel widening (sourcing material from the floodplain) and bed material coarsening. This process has been observed elsewhere, with one recently documented case being the gravel-bed Brenta River in the Italian Alps (Surian and Cisotto, 2007). In this case, bed incision following gravel mining ranged from 1 – 9 m and averaged 5 m. A phase of bank erosion followed, resulting in channel widening. Surian and Cisotto (2007) warned that future bank protection works or removal of gravels from the channel could induce a new incision phase. The Zhuxi-Jiaojiang system is particularly prone to this form of channel adjustment because of the high sediment transport capacity, the current intensity of gravel extraction, and the extensive confinement of the river within rock levees (limiting the supply of sediment from the banks). Reduced sediment transport capacity (through dam construction) could slow this process. However, sediment mobilization is important for maintenance of habitat conditions, so the more appropriate response would be to maintain floods, but manage (i.e. maintain) sediment supply. This could mean cessation of gravel extraction activities, allowing bank erosion to proceed, and augmentation of bedload downstream of dams.

Figure 79. Effects of sediment starvation immediately downstream (top left and top right) and approx. 1 km downstream of reservoir (lower) located on northern tributary of Yong’anxi at 28° 53’ 18” N, 120° 38’ 12” E (location marked on Figure 73).

It seems quite clear that the flow and sediment processes in the Jiaojiang estuary are largely controlled by marine rather than fluvial inputs. The estuary will require regular dredging regardless of any periodic scouring that might be provided by high river flows. During large floods, freshwater will extend further into Taizhou Bay, and sediment will be transported offshore. This may create ecological responses in the estuary and offshore (conflicting anecdotal evidence was provided by local fishermen). During low flow periods, the rate of fine sediment deposition on the bed of the estuary tends to increase. At these times, salt water will migrate further upstream.

Thus, the issues for environmental flows in the estuary are mainly to do with maintaining the mean position of the salt wedge, by maintaining river flows. Inland migration of the salt wedge due to reduced flows will not change the overall character of the estuary, but it may slightly increase the size of the tidal prism. The ecological consequences of this cannot be determined, as it is not known if there are any habitats or biota in the upper Lingjian part of Reach 5 (Figure 73) that are particularly sensitive to salinity change.

4.3 Vegetation

The Jiaojiang Basin lies within the evergreen broad-leaved forest vegetation region of China (Hou, 1983). The natural vegetation in the basin consists of subtropical evergreen broad-leaved forests and needle leaved evergreen forests. Typically central subtropical evergreen broad-leaved forests are distributing in areas at altitudes from 650 m to 1250 m. Mason Pines forests are distributed in hilly regions below 800 m. Chinese fir forests grow at altitudes below 1200 m. Higher altitude mountain regions are occupied by secondary shrubs and herbs. Lowland floodplain areas have been extensively cultivated for rice, wheat and other crops such as fruit and vegetables.

Background searches did not identify any specific information on riverine plant species or communities in the Jiaojiang basin and no species related to riverine systems were identified from lists of protected species (at both the national and regional level). No formal nature reserves or protected areas encompassing riverine habitats were identified within the basin. However, an area of wetland near Linhai city at the confluence of Yong'anxi and Shifengxi was identified. This is characterised by mixed woodland (including Populus sp.) with some open marshland. Useful background information on the ecology of riverine vegetation and its relationship to river flows was obtained from a number of international publications including Naiman and Decamps (1997) and Nilsson and Svedmark (2002).

A number of invasive aquatic plant species are recorded as widespread in southern and eastern China and are likely to occur in the prefecture. These include *Alternanthera philoxeroides* (Alligator weed) and *Eichhornia crassipes* (Water hyacinth) (Xie et al., 2001). *Cabomba caroliniana* (Fanwort) was also recently (1993) recorded in Zhejiang province (Zhang et al. 2003). Alterations to river flow regimes are considered to be important in facilitating the establishment and proliferation of invasive aquatic species (Bunn and Arthington, 2002).

Environmental flow objectives focus upon the flows necessary to maintain existing riparian and wetland plant communities and provide opportunities for recruitment through the maintenance of habitats and, periodic scouring of vegetation. Scouring provides opportunities for recruitment of riparian species on areas of open ground and transfers organic material to the stream. Flows were also considered to prevent encroachment of terrestrial species into the river channels.

4.4 Fish

The most detailed assessment of fish and fisheries available for the Jiaojiang basin comes from a 1971 survey of aquatic resources in Linjiang, by the Zhejiang Fishery Bureau and Zhejiang Institute of Freshwater Fisheries. The findings from this study are outlined in the WET project report "*Background data relevant to ecological assets in Jiaojiang Basin*". In summary, close to 100 species of fish were reported from the basin. Of these just over half (59) were entirely freshwater, nearly a third were from the lower (saline) estuary (24), and approximately 14 were diadromous meaning they migrate between fresh and saltwater. This last group contains many of the species that are of conservation and/or economic importance. Appendix 1 lists the species that were considered in detail in developing the environmental flow recommendations. The inclusion of species in the detailed analysis was based on two factors: conservation and economic significance and the availability of information on biology, habitat requirements etc. One species of particular conservation significance observed during the field surveys was the Chinese Sturgeon, *Acipenser sinensis*. Review of the literature suggest that breeding populations are restricted to the Pearl and Yangtze Rivers (Wei, 1997), although individuals may move in and out of estuaries along the east China coast. In light of this, the species was not specifically considered in developing the flow recommendations.

As a first step the international online “Fishbase” database (www.fishbase.org) was used to establish the availability of information, together with more general online searches of the literature. Fishbase was also useful in formally identifying species from local names as the site provides common species names in numerous languages, including Mandarin. The work of Welcomme et al. (2006) describing fish guilds of tropical floodplain rivers and Dudgeon (1999) describing the dynamics of tropical streams also provided useful background information. It must be stressed at this point that much more information is probably available from internal Chinese reports and from Chinese research/fisheries agencies, but only some of this material was accessible within the available time frame.

Chapter 5: System Hydrology

5.1 Data availability

The Zhuxi-Jiaojiang hydrological system was modelled over the period 1980 – 2006 on a daily time-step using IQQM (Integrated Quantity-Quality Model). Output files were mean daily discharge for the current scenario and a range of future scenarios involving Zhuxi dam operation, environmental flows and construction or modified operation of other dams in the system.

The IQQM model reported at 6 environmental flow nodes (Figure 80). There was a general correspondence between the reporting nodes and the defined environmental flows reaches (Table 85).

Figure 80: Conceptual node diagram for IQQM model.

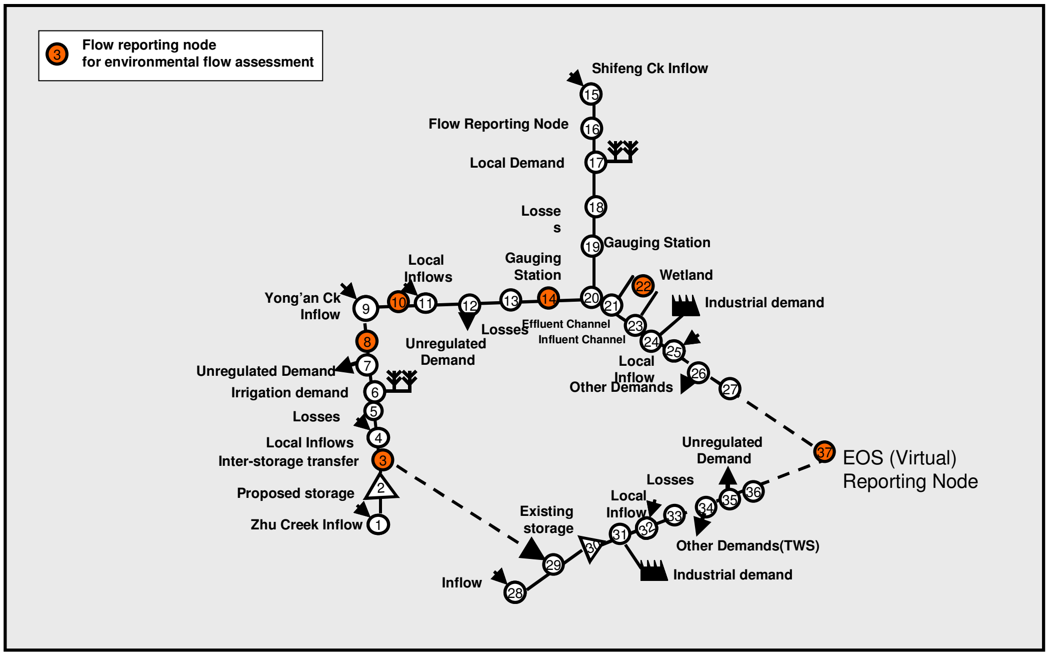


Table 85: IQQM reporting nodes and correspondence with environmental flows reaches

IQQM reporting node	Corresponding section of environmental flows reach
Zhuxi downstream of proposed dam	Upper end of Reach 1
Zhuxi end of Creek	Lower end of Reach 2
Yong'anxi downstream of Zhuxi	Upper end of Reach 3
Yong'anxi upstream of Shifenxi	Lower end of Reach 3
Lingjiang (wetland)	Reach 4 and upper end of Reach 5
Jiaojiang (end of system)	Reach 6

5.2 Methods of data analysis

Hydrology data can be analysed using readily available commercial software, free software (see below for description of three examples) or using purpose-built spreadsheets in Excel.

i. AQUAPAK is a general-purpose program that can be used for the processing of time series data. The software was developed as part of the hydrology text written by Gordon et al. (2004). AQUAPAK handles data based on daily, monthly, and annual periods. Data may be viewed and/or edited via a worksheet (Excel-type) interface. The program can read in a total of 200 x 366 records (i.e. 73,200 data points), which is equivalent to around 200 years of daily data. The program has the capability to calculate virtually any statistic likely to be of interest to environmental flow practitioners. Although the software can be downloaded for free from the SKM website (http://www.skmconsulting.com/Markets/environmental/resource_management/AQUAPAK_Download.htm) SKM requires that users agree to the terms and conditions of a non-commercial software licence.

ii. RAP (River Analysis Package) is a toolbox of quantitative techniques originally developed for environmental flow assessment. RAP includes a 1-D hydraulic model, and a time series analysis module that calculates a range of statistics likely to be of interest to environmental flow practitioners. RAP is one of the Catchment Modelling Toolkit products developed jointly by the CRC for Catchment Hydrology (CRCCH) and CRC for Freshwater Ecology (CRCFE). The Catchment Modelling Toolkit is now supported by the eWater CRC. RAP can be downloaded for free from the eWater website (http://www.toolkit.net.au/cgi-bin/WebObjects/toolkit), but first it is necessary to register (free) and to agree to the terms and conditions of a non-commercial software licence.

iii. IHA (Indicators of Hydrological Alteration) software has been developed by The Nature Conservancy (TNC) as tool for calculating the hydrological characteristics of natural and altered flow regimes. The IHA calculates 33 flow parameters that are thought to have ecological significance. When analyzing the change between two time periods, the software enables users to implement the Range of Variability Approach (RVA) described in Richter et al. (1997). The IHA software also includes calculation of 34 EFC (environmental flow component) parameters, which attempt to automatically identify and compute statistics of hydrological events such as floods and droughts (RVA cannot be applied to EFC). The software can be downloaded for free from The Nature Conservancy website (http://www.nature.org/initiatives/freshwater/conservationtools/art17004.html) but the users manual warns that any commercial use of this software is prohibited without the express, written consent of The Nature Conservancy.

iv. Microsoft Excel is a spreadsheet program within the Office suite of programs. Spreadsheets can be written to undertake any of the calculations performed by AQUAPAK, RAP or IHA, although programming skill will be required in the case of some parameters. The advantage of using Excel (or any other programming language) is that the calculations and graphical outputs can be made specific to the user's needs.

The methodology adopted for the Taizhou pilot study was based primarily on linking hydraulics to ecology. As it was not driven by a hydrological method, there was no need to calculate specific indices, as is done by RAP and IHA. All hydrological analyses undertaken for the Taizhou pilot project were performed using purpose-built Excel spreadsheets.

Hydrological analysis was undertaken: (i) initially, to provide the expert team with an overall understanding of the hydrological characteristics of the streams, (ii) interactively during the environmental flow assessment workshop to characterize the hydrology of particular hydraulically defined events of interest, and (iii) after the flow recommendations had been made to check for compliance.

5.3 Low flows and median flows

Cease to flow is not a characteristic of the Zhuxi-Jiaojiang system, with only a handful of days with cease to flow expected in Zhuxi over the 27 year modelled period (1980 – 2006).

An index of low flows is the 95th percentile flow. There is a marked difference in the magnitude of low flows in the upper part of the system, in Zhuxi, compared to further downstream in the system (Figure 81). The driest period is November to February. Median flows are similarly distributed, with the March to September period consistently showing higher flows throughout the system (Figure 82).

5.4 Flow duration

Flow duration curves summarise the distribution of all flows by depicting the percent of time flows are exceeded. Flow duration curves are well suited to depicting the middle-level flows, with flows falling between the 25th and 75th percentiles (i.e. half of the time) generally covering the normal range of baseflows. Seasonal flow duration curves show the flow distributions for the main seasons defined in the Zhuxi-Jiaojiang system (Figure 83).

5.5 High flows

High flows can be described in terms of the average recurrence interval (ARI) in years. The partial flood series was constructed for each station, using the Cunane plotting position formula (Gordon et al., 2004) (Figure 84). These plots allow estimation of the return period of events of any given magnitude.

Figure 81: Distribution of low flows, represented by 95th percentile daily flows, in the Zhuxi-Jiaojiang system. IQQM modelled current scenario.

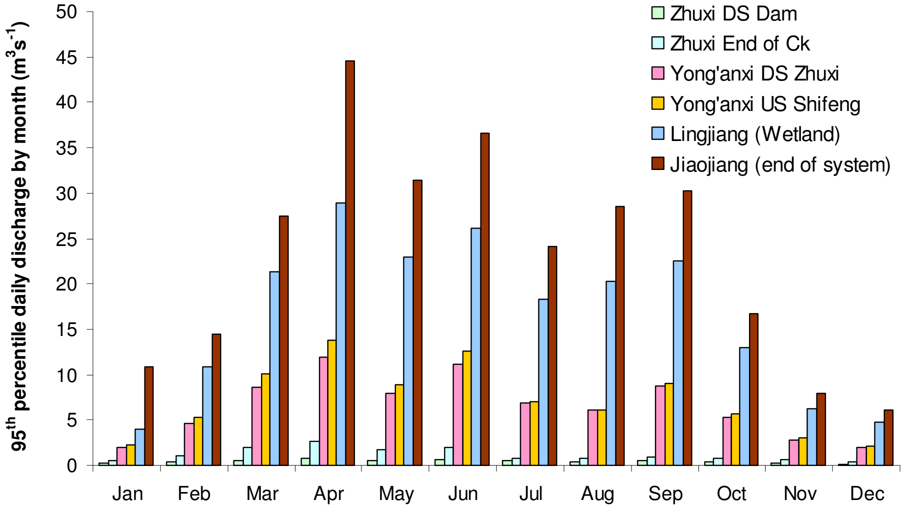


Figure 82: Distribution of median daily flows in the Zhuxi-Jiaojiang system. IQQM modelled current scenario.

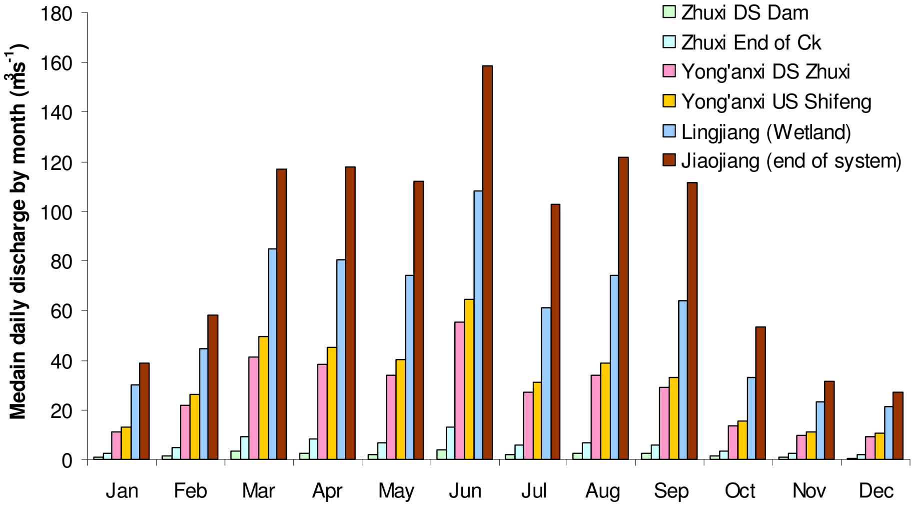


Figure 83: Flow duration curves for mean daily discharge, in the Zhuxi-Jiaojiang system. IQQM modelled current scenario.

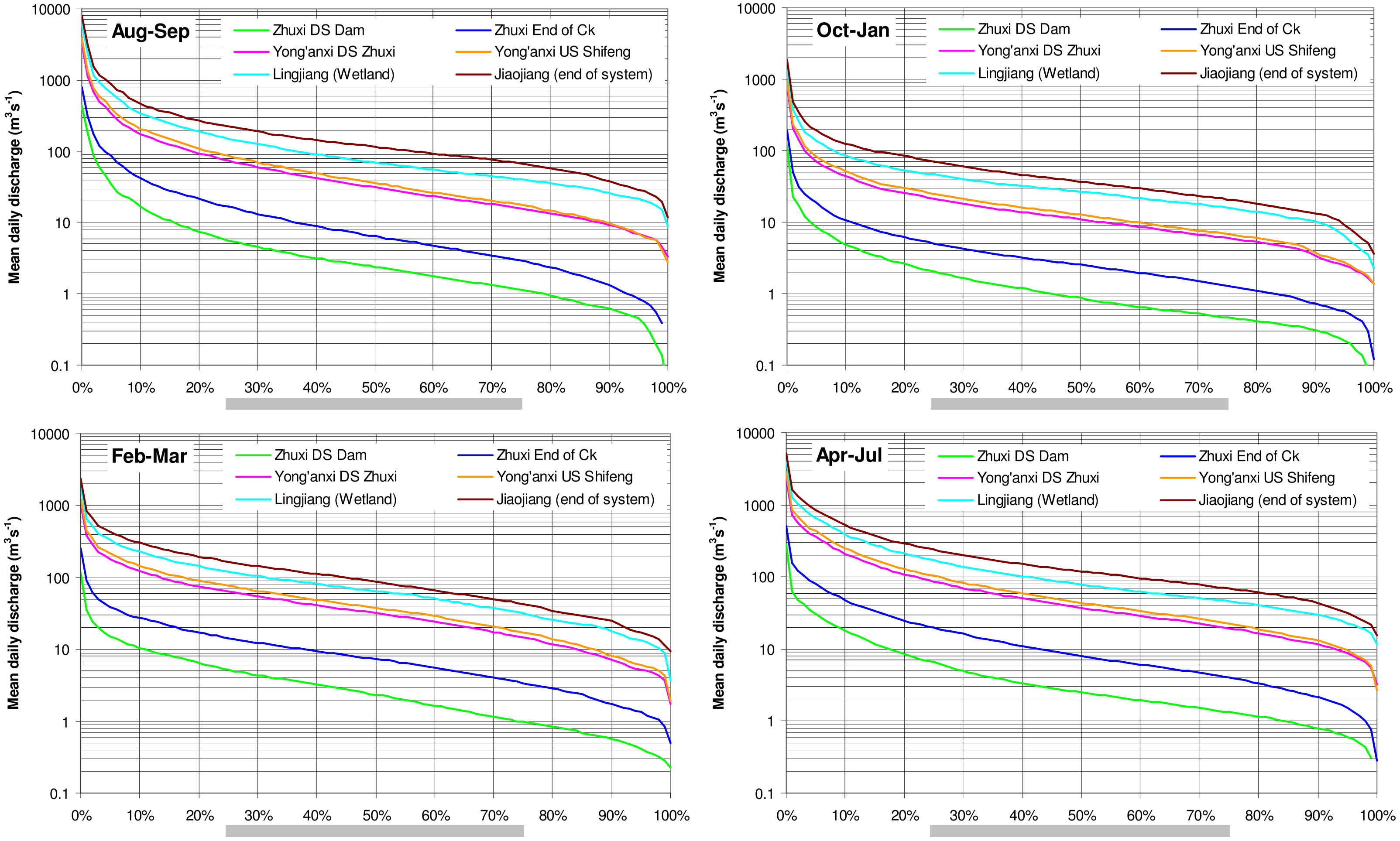
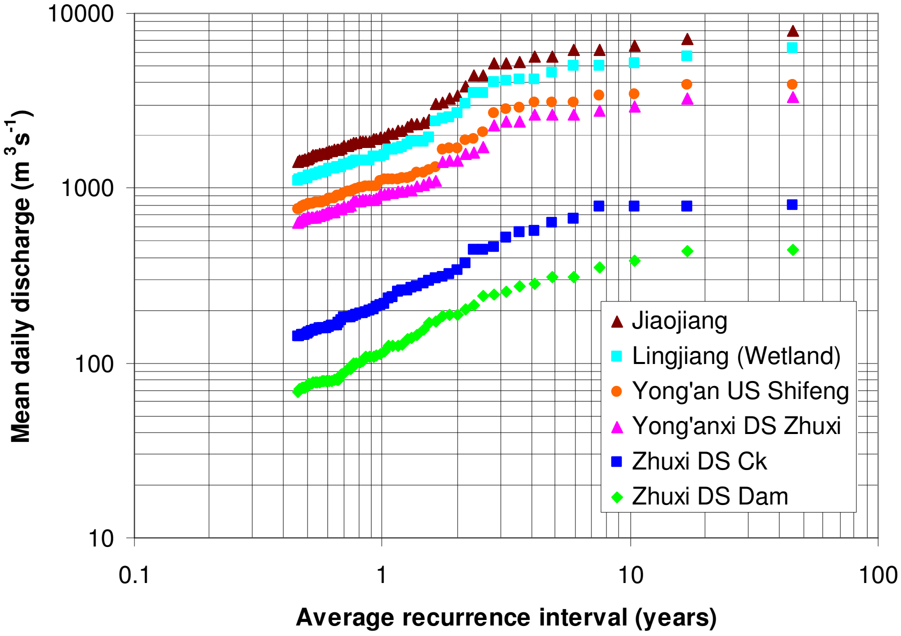


Figure 84: Partial flood series' based on mean daily discharge, in the Zhuxi-Jiaojiang system. IQQM modelled current scenario.



Baxter and Hauer (2000) found that among spawning tributary streams of the Swan River basin, northwestern Montana, the abundance of bull trout redds increased with increased area of alluvial valley segments that were longitudinally confined by geomorphic knickpoints). Among all valley segment types, bull trout redds were primarily found in these bounded alluvial valley segments (BAVS), which possessed complex patterns of hyporheic exchange and extensive upwelling zones (Figure 85).

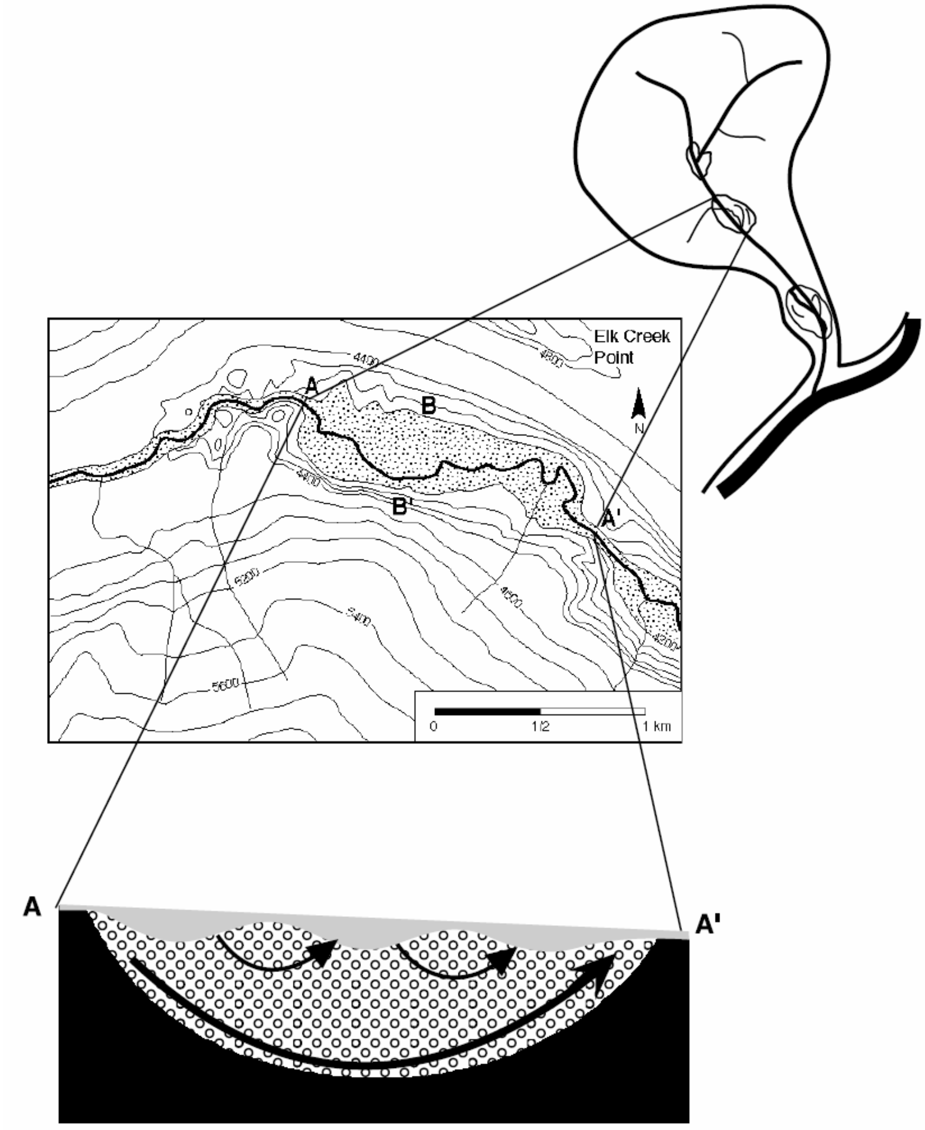
Poole et al. (2006) observed a three layer hyporheic zone in the cobble/gravel-bed Middle Fork Flathead River, Montana. The lower layer (10 m thick) had horizontal hydraulic conductivities of 0.9 cm/s, the middle layer was around 2 m thick and had hydraulic conductivities of 4.3 – 11.6 cm s^{-1}, and the upper layer of 1.6 – 4.3 m thickness had hydraulic conductivities of 1.4 – 2.3 cm s^{-1}.

Baxter and Hauer (2000) estimated vertical hydraulic conductivity (K) for the cobble-bed Swan River basin in Montana ranging from 2.32 × 10^{-6} cm s^{-1} to a maximum of 3.37 × 10^{-1} cm s^{-1}s, a difference of more than five orders of magnitude. Subsurface flow rates were grouped into three classes: low (<0.001 cm s^{-1}), medium (0.001–0.01 cm s^{-1}), and high (>0.01 cm s^{-1}).

For the sand-gravel bed Platte River in south-central Nebraska Chen (2005) measured a mean K value of 0.05 cm s^{-1}. A site in eastern Nebraska had lower mean K values of 0.03 and 0.013 cm s^{-1}, because of fine sediment within the substrate. For this river, Chen (2005) reported that horizontal flow rates exceed vertical rates by a factor of 10.

For the gravel and sand bed Willamette River, Oregon, Fernald et al. (2006) measured horizontal hyporheic flow rates of 0.02 - 0.04 cm s^{-1}.

Figure 85: A bedrock-bounded alluvial valley segment (BAVS) in the Elk Creek drainage basin, Montana. The cross-sectional diagram (A – A' illustrates how reach-scale (large arrow) and bedform-scale (small arrows) hyporheic exchange typically occurs within a BAVS. The stippling denotes the alluvial valley fill. From Baxter and Hauer (2000).



In the Hanford Reach of the Columbia River where hyporheic water discharged into the river channel, Geist (2000) measured rates of upwelling into spawning areas averaged 1200 L m^{-2}·day^{-1}as compared with approximately 500 L m^{-2}·day^{-1} in nonspawning areas.

No attempt was made to measure hyporheic flow rates in the Zhuxi-Jiaojiang system, and there is insufficient information available on which to quantify environmental flow recommendations for this flow component. Studies elsewhere suggest that downriver hyporheic flow rates in gravel/cobble bed streams in the order of 0.001 – 0.1 m s^{-1} should be expected. Thus, for example, an unimpeded gravel layer 2 m thick, and 30 m wide would have the capacity to convey 0.06 – 6 m^3s^{-1}. Conceptually, the reach-scale downstream hyporheic flow rate is limited by the hydraulic constraints of the bedrock-constrained sections of the channel (Figure 85). Subsurface water will pool behind these constrictions, emerging at the surface (upwelling) in a zone of the bed upstream of the constrictions. Thus, at the reach-scale, the upstream ends of BAVS will be losing surface water flow and the downstream ends of BAVS will be gaining.

In managing low flows in Zhuxi (under a future scenario with the dam in place) it will be necessary to adaptively manage the hyporheic flow component. To comply with the surface flow requirement, it may be necessary to release more than the recommended threshold discharge in order to first supply the hyporheic flow component.

5.6 Relationships between daily mean and daily instantaneous peak discharge

Environmental flow assessments are almost universally based on mean daily discharge time series'. This is because mean daily discharge is readily available from the agencies responsible for hydrometrics, the length of the data series is manageable for analysis and plotting, and most programs that calculate hydrological statistics require a fixed time-step, either daily or monthly. Discharge is actually measured at sub-daily time intervals, which may be fixed steps (of say 6 minutes) or variable time intervals that depend on the rate of change in stage height (i.e. less frequent measurements are made when stage height is changing slowly).

When a hydraulic method is used to determine the environmental flow event magnitudes, such as flow required to inundate a bench or reach the top of bank (bankfull) these flows represent instantaneous peak discharges (Q_{PEAK}). It may not be necessary to achieve that instantaneous peak discharge for the entire day, in which case the environmental flow should be specified as both a peak (to achieve the event threshold) and a mean daily discharge (Q_{DAILY}) (as this is the common unit of discharge used by river managers, scientists and stakeholders, and it is the base unit used in hydrologic models, such as IQQM). For events that require the threshold to be achieved for a duration of 1 day or longer (such as pulses and baseflows), the Q_{PEAK} and Q_{DAILY} specification are the same. It should be noted that although the difference between mean daily and daily instantaneous peak is well-known to hydrographers and hydrologists, we are not aware of any published or unpublished environmental flow study that has taken it into account in making the recommendations. Rather, it is assumed that either there is not a large difference between Q_{PEAK} and Q_{DAILY} or the hydraulic events have to be achieved for a minimum duration of one day. For the Taizhou pilot study neither of these assumptions were considered valid, so relationships were developed between Q_{PEAK} and Q_{DAILY}.

Design flood discharges were supplied for the Zhuxi Dam site and for a location close to the end of Zhuxi (Table 86). The catchment area at this location is 337 km^2, compared to the catchment area at the junction of Yong'anxi of 372 km^2. For the IQQM modelled daily flow series' for Zhuxi, discharges corresponding to a range of ARIs from 1 – 20 years were calculated using RAP (Table 87). These two sets of data allow a comparison to be made between peak instantaneous discharge and mean daily discharge for flood events for Zhuxi at the dam site, and at the end of Zhuxi (Figure 86). This comparison results in general relationships for converting Q_{PEAK} (the hydraulically defined threshold) to Q_{DAILY} (for use in IQQM modelling):

- Zhuxi at Dam site (Reach 1): $Q_{PEAK} = 0.2922\ Q_{DAILY} + 23.7$
- Zhuxi at end of creek (Reach 2): $Q_{PEAK} = 0.3445\ Q_{DAILY} + 48.8$

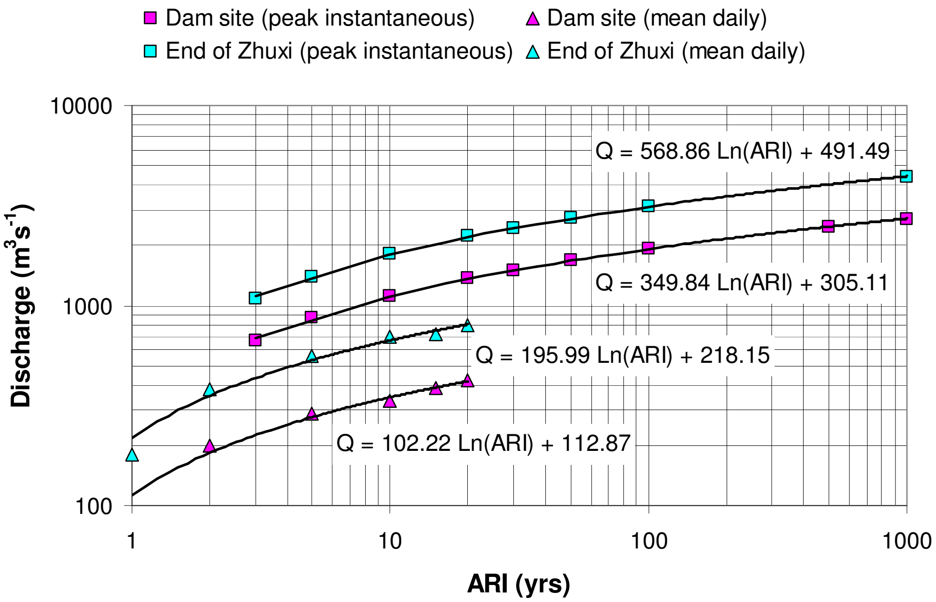
Table 86: Design flood discharges for Zhuxi (annual series).

ARI (Years)	Peak instantaneous discharge (m^3s^{-1})	
	Zhuxi at dam site	Zhuxi near end of creek
1,000	2,707	4,391
500	2,472	
100	1,926	3,124
50	1,684	2,731
30	1,509	2,448
20	1,365	2,214
10	1,115	1,808
5	865	1,402
3	664	1,078

Table 87: Calculated discharges for a range of ARI based on IQQM modelled daily flows for 1980 - 2006 for Zhuxi (partial series for ARI 1-5, annual series for ARI 10-20).

ARI (Years)	Mean daily discharge (m^3s^{-1})	
	Zhuxi at dam site	Zhuxi at end of creek
20	422	792
15	387	720
10	335	695
5	288	559
2	201	383
1	98	181

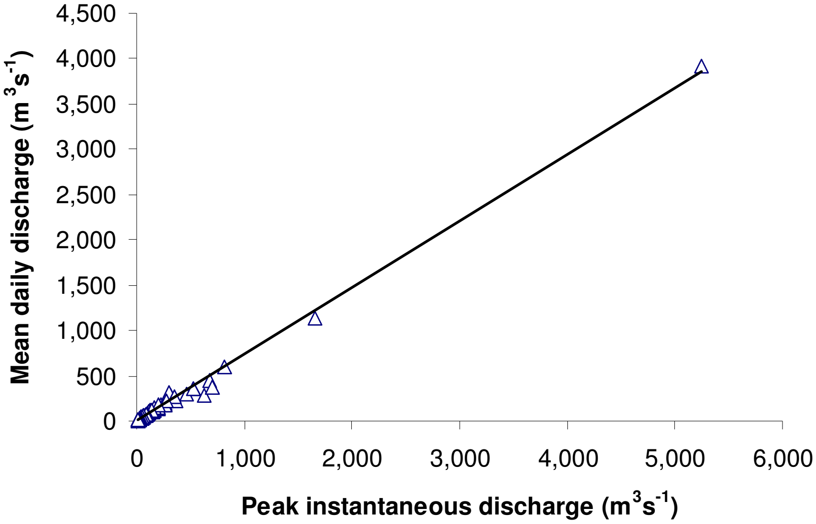
Figure 86: Relationship between mean daily discharge and daily peak instantaneous discharge for Zhuxi.



One year of sub-daily flow observations at Baizhiao gauge on Yong'anxi upstream of Shifengxi junction (Reach 3) were supplied (for 1997). From these data a relationship was established between mean daily discharge and daily instantaneous peak discharge (Figure 87):

- Yong'anxi at Baizhiao (Reach 3): $Q_{PEAK} = 0.7334\ Q_{DAILY} + 3.1$

Figure 87: Relationship between mean daily discharge and daily peak instantaneous discharge for Baizhiao gauge, based on sub-daily recorded flow data from 1997.



There were no data available to determine the relationship between Q_{PEAK} and Q_{DAILY} for Reach 4, and for the tidally influenced Reaches 5 and 6 there was no need to establish this. For Reach 4 the factor was set a little higher than that established for Reach 3 (Figure 87) on the basis that Q_{PEAK} becomes closer to Q_{DAILY} in the downstream direction:

- Lingjiang above Linhai (Reach 4): $Q_{PEAK} = 0.8\ Q_{DAILY}$

5.7 Alternative hydrological analyses

As previously discussed in this report, some environmental flow methodologies are based purely on hydrological analysis, whereby certain hydrological components are statistically described and the environmental flow recommendations are based around preserving those hydrological components considered necessary to maintain ecological health. Most of these methods have some ecological basis, with the flow components being related to certain ecological functions or processes through local empirical studies or literature review. For the Taizhou pilot study there were no such simple flow-ecology relationships available, so this approach was not adopted. However, the Tennant method and IHA method hydrological indices were calculated here mainly as a demonstration of what this achieves, and the data provide a point of comparison for the flow recommendations made for Zhuxi-Jiaojiang based on the adopted holistic hydraulic/hydrologic methodology.

5.7.1 Tennant method

The Tennant method was applied to the modelled discharge time series' for the 6 IQQM nodes (Table 88).

Table 88: Calculated discharges corresponding to the environmental flow – management condition classes defined by Tennant, for the Zhuxi-Jiaojiang system. W = wet season (Oct-Mar), D = dry season (Apr-Sep).

Management condition class	Reach 1		Reach 2				Reach 3		Reach 4 /Reach 5		Reach 6	
	Zhuxi DS Dam		Zhuxi End of Ck		Yong'anxi DS Zhuxi		Yong'anxi US Shifeng		Lingjiang (Wetland)		Jiaojiang (end of system)	
	D	W	D	W	D	W	D	W	D	W	D	W
Flushing or maximum	11	11	28	28	122	122	145	145	240	240	329	329
Optimum range	3.4	5.6	8.4	14	37	61	43	72	72	120	99	164
Outstanding	2.2	3.4	5.6	8.4	24	37	29	43	48	72	66	99
Excellent	1.7	2.8	4.2	7.0	18	31	22	36	36	60	49	82
Good	1.1	2.2	2.8	5.6	12	24	14	29	24	48	33	66
Fair or degrading	0.6	1.7	1.4	4.2	6.1	18	7.2	22	12	36	16	49
Poor or minimum	0.6	0.6	1.4	1.4	6.1	6.1	7.2	7.2	12	12	16	16
Severe degradation	0.0	0.6	0.0	1.4	0.0	6.1	0.0	7.2	0.0	12.0	0.0	16

5.7.2 IHA

The IHA program allows users to adjust the thresholds used to define events. As there was no ecological basis for selecting particular thresholds on the Zhuxi-Jiaojiang system, the IHA was run using the default values. The analysis was run only for four flow time series' – the ones corresponding to the environmental flow reaches. The IHA program calculates statistics according to 5 Parameter Groups (Table 89, Table 90, Table 91) and EFC Low Flows (Table 92) and EFC Parameters (Table 93). The EFC Low flows parameter is described by The Nature Conservancy (2007a) as "Mean or median of low flows" (it is not stated which one is calculated, the mean or the median?, and this is not a selectable option). In the program, low flows are flows between the lowest 10th percentile and the 50th percentile, but there are other conditional filters associated with rates of rise and fall.

Table 89: IHA Parameter Group #1 - Monthly mean discharge (m^3s^{-1}).

	Reach 1 Zhuxi DS Dam	Reach 2 Zhuxi end of creek	Reach 3 Yong'anxi US Shifengxi	Reach 4 Lingjiang (Wetland)
January	1.1	2.7	12.3	29.6
February	1.2	4.1	23.8	37.8
March	3.4	8.9	48.5	88.6
April	2.9	10.4	53.7	90.2
May	2.1	7.4	43.6	76.6
June	4.2	13.2	68.0	100.7
July	1.8	5.6	35.1	64.7
August	2.1	7.0	37.6	71.6
September	2.3	5.8	31.8	61.7
October	0.9	2.9	15.2	32.5
November	0.8	2.3	11.2	24.9
December	0.6	2.0	11.4	19.9

Table 90: IHA Parameter Group #2 - Magnitude and duration of annual extreme water conditions (all discharge indices in m^3s^{-1}) and IHA Parameter Group #3 - Timing of annual extreme water conditions (Julian day).

	Reach 1 Zhuxi DS Dam	Reach 2 Zhuxi end of creek	Reach 3 Yong'anxi US Shifengxi	Reach 4 Lingjiang (Wetland)
Parameter Group #2				
1-day min.	0.3	0.6	3.0	9.0
3-day min.	0.3	0.6	3.1	9.8
7-day min.	0.3	0.6	4.0	10.9
30-day min.	0.5	1.3	6.9	14.5
90-day min.	1.4	3.5	17.7	36.8
1-day max.	137	261	1230	1836
3-day max.	73	155	849	1277
7-day max.	40	98	558	909
30-day max.	19	48	247	395
90-day max.	11	29	152	241
No. of zero days	0	0	0	0
Base flow index	0.058	0.051	0.046	0.078
Parameter Group #3				
Date of min.	352	210	1	2
Date of max.	214	226	219	213

Table 91: IHA Parameter Group #4 - Frequency and duration of high and low pulses and IHA Parameter Group #5 - Rate and frequency of water conditions change. All discharge indices (including rates) in m^3s^{-1}. Duration in days.

	Reach 1 Zhuxi DS Dam	Reach 2 Zhuxi end of creek	Reach 3 Yong'anxi US Shifengxi	Reach 4 Lingjiang (Wetland)
Parameter Group #4				
Low pulse count	8	7	7	7
Low pulse duration	6.5	5	7	6
High pulse count	21	18	16	15
High pulse duration	3	3.5	4	3.5
Low Pulse Threshold	0.8	2.3	12.4	27.2
High Pulse Threshold	4.4	12.4	65.0	110.1
Parameter Group #5				
Rise rate	0.4	1.2	5.9	7.9
Fall rate	-0.3	-0.7	-2.8	-5.7
Number of reversals	128	117	106	124

Chapter 6: Environmental Flow Objectives

6.1 Overarching objectives

Based on the identified environmental assets, the environmental flow recommendations presented in this report are designed to:

i. Maintain fish diversity and abundance

ii. Maintain subsistence and commercial fisheries

iii. Maintain water quality at a level capable of supporting objectives 1 and 2 together with existing uses of the river.

iv. Maintain riparian vegetation in its current form in riparian and low-lying floodplain habitats.

v. Maintain geomorphic processes that are required to support objectives 1 - 4.

Table 92: EFC Low flows – "Mean or median of low flows" (low flows are flows between the lowest 10th percentile and the 50th percentile) (m^3s^{-1}).

	Reach 1 Zhuxi DS Dam	Reach 2 Zhuxi end of creek	Reach 3 Yong'anxi US Shifengxi	Reach 4 Lingjiang (Wetland)
January	0.9	2.7	14.3	29.8
February	1.0	3.2	18.4	31.1
March	1.5	4.9	26.0	46.4
April	1.5	4.9	29.2	52.2
May	1.2	4.1	24.7	47.1
June	1.3	4.0	21.4	45.1
July	1.1	2.7	15.0	38.2
August	1.2	3.4	18.8	42.8
September	1.3	3.3	19.0	41.4
October	0.9	2.5	13.2	28.5
November	0.8	2.0	10.1	26.7
December	0.6	2.5	11.9	23.1

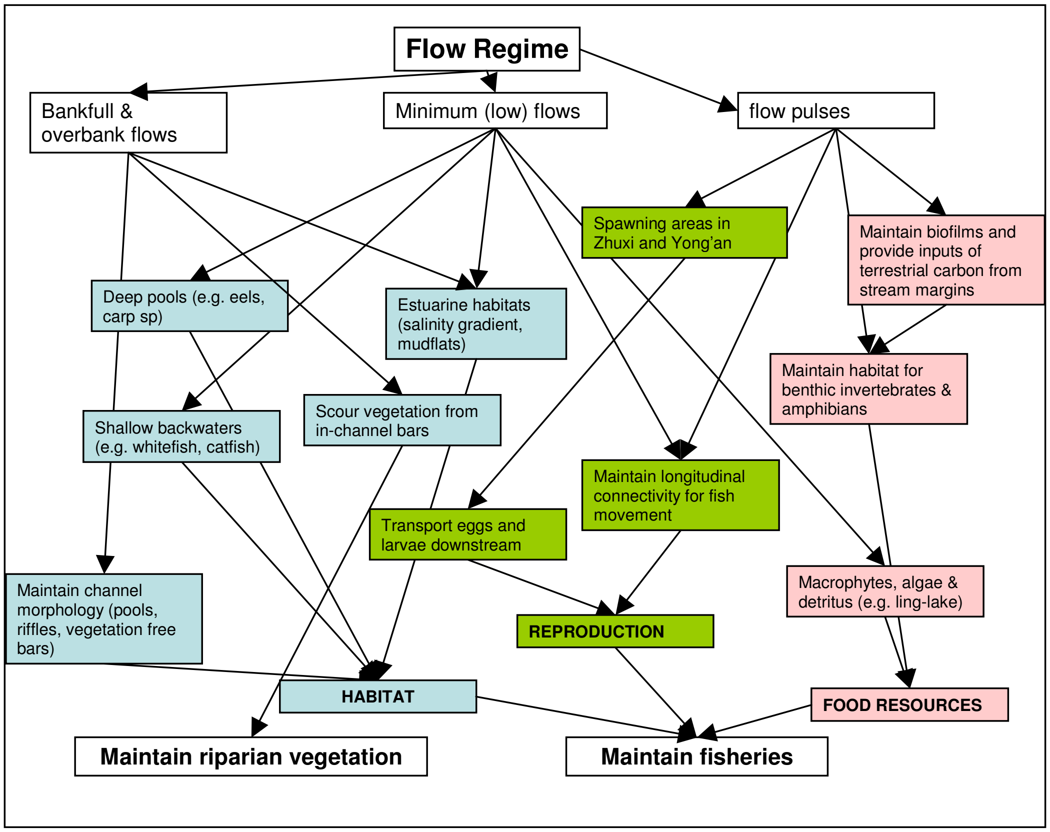
Table 93: EFC Parameters. Frequency is mean number of events per year, timing is Julian Days, duration in days, magnitudes (including rates) in m^3s^{-1}.

	Reach 1 Zhuxi DS Dam	Reach 2 Zhuxi end of creek	Reach 3 Yong'anxi US Shifengxi	Reach 4 Lingjiang (Wetland)
Extreme low peak	0.3	0.6	3.7	10.7
Extreme low duration	3	4.5	6	2
Extreme low timing	7	219	343	350
Extreme low freq.	2 per yr	2 per yr	1 per yr	2 per yr
High flow peak	10	26	129	209
High flow duration	6	5.5	6	6
High flow timing	170	172	178	158
High flow frequency	19 per yr	18 per yr	17 per yr	17 per yr
High flow rise rate	3.9	8.7	43.4	71.7
High flow fall rate	-1.8	-3.8	-19.8	-31.4
Small Flood peak	221	394	1,784	2,997
Small Flood duration	13	15	15	16
Small Flood timing	233	232	213	213
Small Flood freq.	1 in 1 yr	1 in 1 yr	1 in 2 yr	1 in 2 yr
Small Flood rise rate	57	118	723	1172
Small Flood fall rate	-23	-43	-131	-197
Large flood peak	438	793	3,794	6,012
Large flood duration	25	23	16	26
Large flood timing	247	244	243	238
Large flood freq.	1 in 10 yr	1 in 10 yr	1 in 10 yr	1 in 10 yr
Large flood rise rate	146	244	715	1,139
Large flood fall rate	-20	-45	-365	-400

6.2 Linking multiple flow components

Flow related objectives pertaining to geomorphology, vegetation, fish and water quality were determined independently from one another for each reach. Also, associations were made between each objective and the components of the flow regime on which it depends. These associations are broadly represented as a conceptual model of flow/ecology/geomorphology relationships (Figure 88). This model illustrates the role of multiple specific flow components in achieving the overall flow objectives. Note that whilst individual flow components may relate to several objectives, typically there is one objective that acts as the key constraint, and during the environmental flow assessment procedure, this was noted as the controlling objective.

Figure 88: Conceptual diagram showing the links between individual flow related objectives and multiple specific flow components.



6.3 Objectives related to flow components

Environmental flow objectives were formulated for geomorphological (Table 94), vegetation (Table 95), and fish (Table 96) aspects. Each geomorphological objective was linked to critical ecological processes; each ecological objective was included on the basis of its perceived importance to maintaining ecological function, as derived from literature review, survey and informal discussions with locals, and field observations. A hydraulic criterion was assigned for each geomorphological and ecological objective as the means of deriving a flow recommendation to satisfy the objective.

Table 94: Flow components relevant to geomorphological objectives.

ID	Objective	Flow component	Hydraulic criteria	Timing	Reach	Reference
1a	Maintain channel form	Bankfull	Morphologically defined levels	anytime	1, 2, 3, 4	Gippel, 2001; Gippel, 2005
1b	Flush fine sediment from surface of bed	Low flow pulse and High flow pulse	Critical shear stress to mobilise silts	Low flow and High flow	1, 2, 3, 4	Gippel, 2001; Gippel, 2005; Wu and Chou, 2004
1c	Mobilise coarse bed sediments	High flow pulse/Bankfull	Critical shear stress to mobilise >50% of bed material	anytime	1, 2, 3, 4	Gippel, 2001; Gippel, 2005
1d	Maintain channel form and key habitats	High flow pulse/Bankfull	Morphologically defined levels	anytime	1, 2, 3, 4	Gippel, 2001; Gippel, 2005

Table 95: Flow components relevant to vegetation objectives.

ID	Objective	Flow component	Hydraulic criteria	Timing	Reach	Reference
2a	Scour vegetation from gravel bars and transfer organic material to the stream	High flow pulse	Sufficient to scour vegetation	high flow season (Apr - Sep)	1, 2, 3	
2b	Maintain vegetation neighbouring the river channels (riparian vegetation)	Overbank flow	Morphologically defined levels	anytime	1, 2, 3, 4, 5	Naiman and Decamps, 1997
2c	Prevent encroachment from terrestrial species into river channels (e.g. *Salix* sp.)	Bankfull	Critical shear stress	anytime	1, 2, 3	
2d	Maintain floodplain wetland communities (perennial and annual species)	Overbank flow	Morphologically defined levels	high flow season (Apr -Sep)	1, 2, 3, 4, 5	

Table 96: Flow components relevant to fish objectives. D = depth, V = velocity.

ID	Objective	Relevant species	Flow component	Hydraulic criteria	Timing	Reach	Reference
3a	Maintain sufficient water depth in pools for large bodied fish	Pool Guild (e.g. Eels, *Spinibarbus*, Carp species)	Low flow	D > 1.5 m in pools in reaches 1 – 3 D > 3 m in reaches 4 & 5	Oct-Mar	1, 2, 3, 4, 5, 6	Welcomme, 2006
3b	Maintain sufficient depth in riffles and in depositional habitats out of the flow	Pool Guild (e.g. whitefish, catfish) and Riffle species	Low flow	D > 0.2 m	Oct-Mar	1, 2, 3, 4, 5, 6	
3c	Localised movement of resident fish	Whitefish, catfish	Low Flow Pulse	D > 0.2 m over riffles	Oct-Mar	1,2,3	
3d	Maintenance of benthic habitats &hyporheic flushing	Spinibarbus, Misgurnus mizolepis	Low flow Pulse	Sufficient to flush fine sediments from gravel	Oct-Mar	1,2,3	
3e	Flows to provide habitat during the high flow period, to induce spawning of grass, silver and bighead carp & to maintain transport of semi-buoyant eggs within the water column	Grass, silver, bighead carp	High flow	Mean V >0.15 - 0.25 ms^{-1}	Apr-Sep	1,2	Tang et al, 1989
3f	Stimulate spawning migration & maintain longitudinal connectivity (estuary to headwaters)	Anadromous and Potamodromous guilds. (e.g. carp, *Coilia ectenes*, *Macrura reevsii*)	High flow pulse	Inundate barriers. Increase D >0.25 m over riffles	April	1,2,3	Welcomme, 2006; Dudgeon, 1999;
3g	Provide access to floodplain habitats	Species that spawn on floodplains (no local information supplied).	Overbank flow	Sufficient depth to inundate low lying areas of the floodplain such as wetlands	Anytime	2, 3, 4, 5, 6	Welcomme, 1985; Welcomme, 2006
3h	Flow to prevent increases in the upstream intrusion of saline water during low flows	Freshwater estuarine guild (e.g. *Lateolabrax japonicus*)	Low flow & High flow	Non-hydraulic criteria	All year	4, 5, 6	Welcomme, 2006, Guan et al., 2005
3i	Flow to maintain salinity and sediment dynamics at the mouth of the estuary. Physical habitat is mudflats & river-channel	Estuarine Guild (e.g. *Acanthopagrus* schlegelii; *Mugil* spp.; purple spotted mudskipper)	Low Flow	Complex hydro and sediment dynamics. Estuarine hydrodynamic modelling	Summer	5, 6	Welcomme, 2006, Guan et al., 1998; Guan et al., 2005
3j	Flow to maintain salinity & sediment dynamics at the mouth of the estuary. Physical habitat is mudflats & river-channel	Estuarine Guild (e.g. *Acanthopagrus* schlegelii; *Mugil* spp.; purple spotted mudskipper)	High Flow	Complex hydro and sediment dynamics. Estuarine hydrodynamic modelling	Summer	5, 6	Welcomme, 2006, Guan et al., 1998; Guan et al., 2005

Chapter 7: Specifying Flow Components Using Hydraulics and Hydrology

7.1 Principles of hydraulic models

Hydrology of flowing water is concerned with rates of flow (or discharge), expressed in m^3s^{-1}, and the way the flow varies through time. Hydraulics of flowing water is principally concerned with depth (m), velocity (ms^{-1}), and shear stress (Nm^{-2}).

In order that environmental flow recommendations can be implemented by river managers (or dam operators), each component making up the regime has to be specified as a discharge value, with associated frequency, timing and duration. While it may be possible to state with a high degree of confidence that certain ecological processes are associated with certain flow components (e.g. low flows, high flow pulses, bankfull flows etc.), it is rarely possible to make a confident direct link from an ecological process to a specific flow magnitude. Rather, the ecological processes of interest are more readily defined as a depth of water in the channel (e.g. a minimum depth over riffles to sustain macroinvertebrates), an elevation in the channel (e.g. corresponding to the location of a particular flow dependent vegetation community, or the top of the banks), maximum or minimum velocities (e.g. limits of swimming capability of a fish species), or shear stresses (e.g. sufficient to mobilize bed material, or scour vegetation from the bed). Thus, the magnitude of flow components is derived from hydraulic information. Knowledge of the channel morphology and roughness allows the hydraulic characteristics to be described for any given flow (and vice-versa). A hydraulic model provides the numerical link between hydraulics and flow.

Hydraulic models can be 1-D, 2-D or 3-D, in order of complexity to set up and run, and in order of the detail they provide. For most environmental flow applications, 1-D models are considered adequate. It is preferable to model the hydraulics over a reach of at least a few 100 metres long. This allows consideration of conditions as the morphology changes (e.g. pools and riffles), and the models account for the longitudinal interactions through the reach. For example, a riffle usually acts as the hydraulic control over flow for a certain distance upstream, and all areas upstream from this control point will fall under its influence. The most popular 1-D model for application to environmental flow studies is HEC-RAS, but there are other alternatives available.

HEC-RAS has been developed for the U.S. Army Corps of Engineers. It is also available for download (http://www.hec.usace.army.mil/SOFTWARE/hec-ras/) and use by individuals outside of the Corps of Engineers without charge. HEC will not provide user assistance or support for this software to non-Corps users. However, certain organizations provide the program, documentation, and support services for a fee. Downloading, installing, and using the HEC-RAS software indicates the user’s acceptance of HEC's Terms and Conditions for use of HEC Software. These Terms and Conditions do not exclude commercial use. The basic computational procedure in HEC-RAS is based on the solution of the one-dimensional energy equation. Energy losses are evaluated by friction (Manning’s equation) and contraction/expansion (coefficient multiplied by the change in velocity head). The momentum equation may be used in situations where the water surface profile is rapidly varied. These situations include mixed flow regime calculations (i.e. hydraulic jumps), hydraulics of bridges, and evaluating profiles at river confluences (stream junctions. Running a HEC-RAS model requires a series of professionally surveyed cross-sections through the reach of interest (i.e. the cross-sections must have a common datum).

The Hydraulic Analysis Module in the (free to download) River Analysis Package (RAP) (http://www.toolkit.net.au/cgi-bin/WebObjects/toolkit) allows the importation of HEC-RAS cross-section data, as well as user input cross-section data, to create a 1-D hydraulic model of a river reach. The FldWav (USA National Weather Service) 1-D hydraulic model is used to calculate a hydraulic parameters in the reach for multiple alternative discharges. The hydraulic parameters are presented as a rating curve against discharge. If a time series of discharge is provided this can be converted to a time series of hydraulic parameters that can be subsequently analysed in the RAP Time Series Analysis Module.

It is not always feasible to undertake channel surveys or to develop a reach-scale hydraulic model, either due lack of resources to hire surveyors, or lack of personnel with qualifications in hydraulics. However, it is feasible for non-expert surveyors to undertake field cross-sections using simple methods, such as rod and level, tape measure, or range finder and inclinometer. In this case, one or more cross-sections are surveyed at the identified hydraulic control points (riffle crests), and the hydraulics of each cross-section is determined separately. Rather than use HEC-RAS or RAP to analyse the hydraulics of single cross-sections, a simpler alternative is the program WinXSPRO.

WinXSPRO is a software package designed to analyze stream channel cross-section data for geometric, hydraulic, and sediment transport parameters. WinXSPRO was specifically developed for use in high-gradient streams (gradient >0.01) and supports four alternative resistance equations for computing boundary roughness and resistance to flow. Cross-section input data may be from standard cross-section surveys using a rod and level or sag-tape procedures.

WinXSPRO was developed by the USDA Forest Service, Stream Systems Technology Center. WinXSPRO is Government-produced software in the public domain and is provided "as-is" without warranty of any kind, including, but not limited to, the implied warranties of merchantability and fitness for a particular purpose. The user assumes all responsibility for the accuracy and suitability of this program for a specific application. Limited technical support is available from USDA Forest Service, Washington Office Watershed, Fish, Wildlife, Air, & Rare Plants Staff, Streams Systems Technology Center, Fort Collins, CO. A copy of WinXSPRO can be downloaded free of charge from http://www.stream.fs.fed.us/publications/winxspro.html.

In some cases it may not be possible to undertake cross-section surveys. For example, the river may be too deep to allow easy access, or there may be time and resource constraints. In this case, it may still possible to obtain useful hydraulic information. The most likely source of existing hydraulic information is a discharge gauge. Established flow gauges are periodically “rated”, which involves hydrographers carefully measuring the discharge and noting the height of the water (the “stage height”). Over time a “rating curve” is built-up, which is an empirical relationship between discharge and the stage height at the gauge location. Gauges usually have cross-section data available, so by calculating cross-sectional area, mean velocity and shear stress can be estimated for any selected stage height. The main caution with gauge hydraulic relationships is that gages are not necessarily located in a typical section of the river; rather, hydrographers intentionally try to select a stable cross-section so that the rating curve is stable through time (reducing the work required to update the rating curve over time). Also, it would be coincidental if the gauge was located at a point on the river that was of particular interest to the environmental flows assessment.

Some river gauges do not measure discharge but they do measure stage height. These gauges have never been rated. Data from stage-only gauges can provide valuable information on the variation in river height over time. If a cross-section is available, surveyed to the same datum, a rating curve can be derived through a program such as WinXSPRO.

When undertaking a hydraulic analysis as part of an environmental flow assessment, it is important to seek out any local information that relates the height of features of ecological interest (such as the sill of a wetland) to the flow of the river. For example, local residents may be able to indicate the relative heights that the most recent (or most memorable) floods reached, and an examination of the flow record will indicate the peak discharge for those events. If the heights of features of ecological interest (e.g. wetland or floodplain surface) can be related to these culturally related flood heights (e.g. heights reached on a bridge, over a road, or within a building) then the discharge required to inundate these features can be estimated by examining the flow record.

7.2 Specifying ecologically meaningful hydraulic thresholds

There is no point developing hydraulic models unless the ecological processes of interest can be expressed in hydraulic terms, preferably as a threshold (or range of) depth, velocity, or shear stress. This is the task of the expert panel. For example, the vegetation specialist should be able to note the position of plants of interest on the surveyed cross-sections, and might have empirical knowledge of the threshold shear stress that will dislodge certain types of plant; the macroinvertebrate specialist will be able to specify the depth of water required over riffles in order to maintain the community; the fish specialist will know something about the hydraulic preferences of key species or guilds at different times of the year; and the geomorphologist will have measured particle size and know the shear stress required to mobilize a certain proportion of the bed material. Hydraulic criteria were developed for geomorphological (Table 94), vegetation (Table 95), and fish (Table 96) objectives for the Taizhou pilot study.

7.2.1 Mobilisation of bed material

For sediment mobilisation, shear stress thresholds were computed by applying Shields Critical Shear Stress Method (Gordon et al., 2004, p.193-195). Two generic sediment thresholds were computed, specifically the shear stress (τ) required to: a) flush fine silt from a gravel surface ($\tau_c = 0.34\ D$); b) to mobilise the coarse bed material ($\tau_c = 0.97\ D$). Bed material particle size (D in mm) was characterised at four sites (representing Reaches 1 and 3) using a Wolman Pebble Count. The equation above for coarse bed material mobilization is appropriate for “normal settled bed” if the particles are spherical and for “highly imbricated bed” for flat shaped particles. The bed materials of Zhuxi Creek were deemed to be a mix of spherical and flat shaped particles and moderately imbricated. The shear stress for bed mobilization was calculated for D_{50} (median particle size) and D_{16} (16% of the distribution of sizes is finer than this size). The fine sediment flushing shear stress was calculated for D_{50}.

7.2.2 Vegetation disturbance

For local vegetation, data on thresholds for disturbance were not available. As an alternative, the thresholds for removal of grasses and rupture ('lodging') of macrophytes were computed. The minimum shear stress required to impact the least hardy of grasses (i.e. poorly established bunch grass) is 80 N/m^2 (Reid, 1989; Hudson, 1971). The discharge required to rupture macrophytes was computed by application of Groeneveld and French's (1995) relationship. The diameter of the macrophyte stems was set, as recommended by Groenveld and French (1995), to 11.9 mm. Two thresholds were then evaluated to give a 95% and 99.9% chance of stem rupture respectively. The thresholds are reported as a discharge (Q) required for the product of flow depth and velocity to exceed either 0.152 ($Q_m^{95\%}$ - referred to here as Q95) or 1.52 ($Q_m^{99.9\%}$ - referred to here as Q99.9). Depth in this context was assumed to be hydraulic depth (ratio of cross-sectional area to top width), rather than maximum depth.

Shrubs and small trees are present on the margins of the channels, and it is ecologically desirable to occasionally check their growth to prevent them colonizing the channel. There are no published data available on which to base an index for removing shrubs and small trees, so here we assumed that the shear stress to remove grass and macrophytes would disturb shrubs, as shrubs are less flexible and present a greater drag on the flow (due to larger projected area) - countering this is the possibility of greater rooting strength. It is emphasised that the removal of vegetation can only be predicted as a probability, and that for any given event only a proportion of vegetation will be disturbed. Vegetation may remain undisturbed due to variations in flow velocities within a stream, the stability provided by the substrate in which plants grow or the path taken by debris entrained by the flow. For this reason, this criterion is expressed in terms of 'checking the growth of' or 'disturbing' shrubby vegetation. It is not intended to represent the removal of all shrubby vegetation.

7.2.3 Depths and velocities for biota

A number of depth and velocity thresholds were defined for fish (Table 96). These were drawn from the literature as being suitable for the guilds present in the Zhuxi-Jiaojiang system.

7.2.4 Channel maintenance

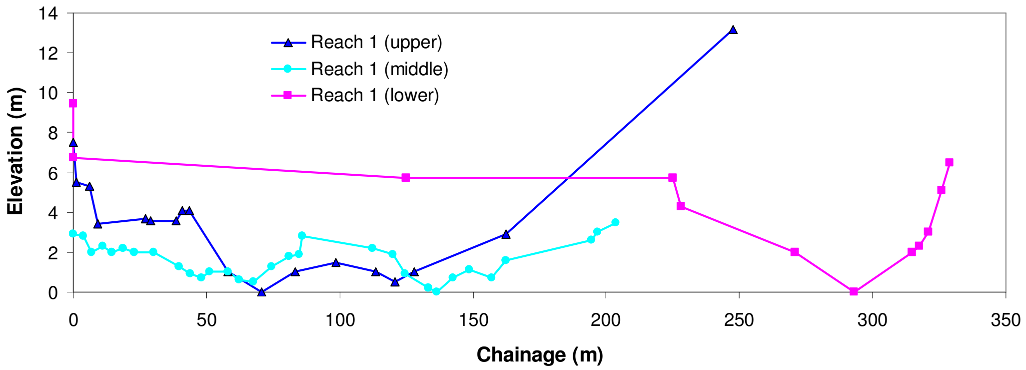
Channel maintenance was assumed to be associated with bankfull flows. Morphological bankfull level was determined in the field and noted on the cross-section surveys.

7.3 Hydraulic models

7.3.1 Reach 1 and Reach 2

Hydraulic models were developed for Reach 1 by undertaking 2 cross-section surveys in the field using a range finder and inclinometer, and analyzing the data in WinXSPRO. A third cross-section located at the downstream end of Reach 1 was used to generate a hydraulic model for Reach 2 (Figure 89). The model was run assuming the resistance equation of Thorne and Zevenbergen, and using the mean reach gradient derived from the SRTM DEM. One cross-section was located near the proposed dam site, and the other was mid-reach. Results from the mid-reach cross-section were regarded superior to those from the upper cross-section, because the mid-reach cross-section was located on a better-defined riffle crest. The hydraulic models are regarded as relatively low accuracy for low discharges and depths. This is because of the relatively low resolution of the survey, and the high sensitivity of the predicted flows to the roughness factor. Thus, the results for low flows and low flow pluses (driven by fish depth and velocity criteria) should be interpreted with a degree of caution. Because of this problem the low flows and high flows (the baseflow components) were also estimated using a hydrological index - equivalent to the flow exceeded 75% of the time for the defined season. This reflects the low end of the normal baseflow range.

Figure 89: Three surveyed cross-sections on Zhuxi. Arbitrary datum in each case. Reach 1 (lower) is near the upper boundary of Reach 2.



The hydraulic models generated rating curves of mean velocity, mean shear stress and discharge against depth (Figure 90). Bankfull level was defined using morphological criteria – as defined in the field. These rating curves were used to convert each of the defined geomorphological, fish and vegetation hydraulic indices into discharge values. The discharges corresponding to the geomorphic and vegetation indices are provide in Table 97. The fish indices were more straightforward, being re based on simple depth and velocity criteria. The magnitudes for the environmental flow components were selected from these hydraulically modelled discharge values.

The hydraulic models predict increasing bankfull discharge downstream, which is the expected pattern. Mobilisation of a high percentage of the bed material and removing stout shrubs and small trees requires overbank flows. A percentage of the bed material is mobilized at sub-bankfull flows, so pulses of any magnitude will achieve some bed mobilization. Growth of vegetation on bars is likely to be frequently checked, as small pulses are predicted to achieve this. Macrophytes will be kept in check by sub-bankfull flows.

7.3.2 Reach 3

This reach was not physically surveyed (due to excessive water depth). However, a gauge is located at the downstream end of this reach (Baizhiao). A cross-section and rating curve were obtained for this gauge. The cross-section showed well-defined benches, and it was assumed that the top right bank corresponded to bankfull (Figure 91). At cease to flow there was depth of 1.74 m of water at the cross-section. The reason for this is unknown, but most likely it relates to a downstream control.

Figure 90: Hydraulic relationships derived for three cross-sections in Zhuxi, a) Reach 1 upper-reach cross-section , b) Reach 1 mid-reach cross-section and c) Reach1/Reach 2 boundary cross-section. BF is depth corresponding to morphologically defined bankfull.

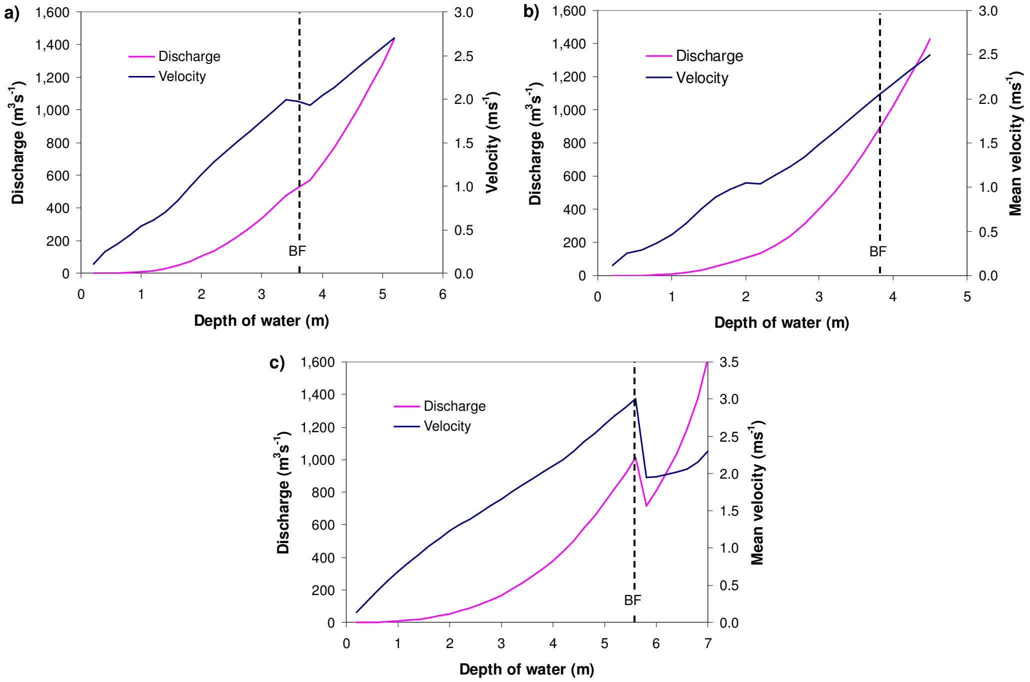


Table 97: Flow threshold magnitudes calculated from hydraulic models to achieve geomorphological and vegetation objectives.

Geomorphological/vegetation indices	ID	Flow threshold magnitudes (m^3s^{-1})		
		Reach 1 (upper)	**Reach 1 (mid)**	**Reach 2 (upper)**
Flushing of fines from the surface	1b	85	208	45
Mobilisation of 16% of the bed material	1c	69	310	83
Mobilisation of 50% of the bed material	1c	1,013	>1,430	654
Morphological bankfull	1a, 1d, 2b, 2c, 2d	524	878	1,011
Q95 - 95% chance of macrophyte stem rupture (scour vegetation from bars)	2a	4.9	8.0	2.3
Q99.9 - 99.9% chance of macrophyte stem rupture (shrub disruption)	2a, 2c	149	288	80
Scour grass (minimum) (shrub/tree disruption)	2c	1,900	>1,500	>3,000

7.3.3 Reach 4

This reach was not physically surveyed (due to excessive water depth). However, an important wetland was observed on the left bank of Lingjiang just downstream of Shifengxi. Local knowledge suggested that the wetland was inundated at a sill level of 7.5 m (relative to sea level).

A tide gauge is located just downstream of the wetland (Linhai chaowei). It is of interest that the median tidal range at this gauge from 1996 to 2006 was 5.15 m (Figure 92), which is greater than the mean tidal range of 4 m reported by Guan et al. (2005) for the tide gauge at Haimen near the mouth of the estuary. Tidal amplification is to be expected in this estuary due to the narrowing of the channel cross-section in the upstream direction, so the entire Lingjiang reach up experiences a strong daily variation in water level.

Figure 91: Cross-section at Baizhiao gauge, showing discharge corresponding to morphologically defined levels. Note that there is a 1.74 m depth of water when the river ceases to flow. Datum of elevation is unknown.

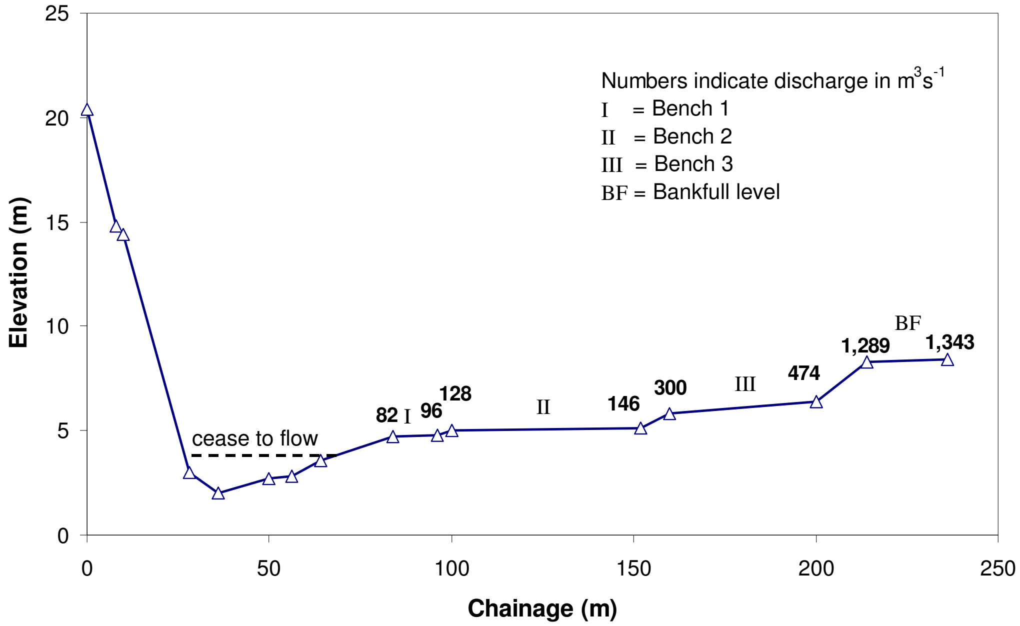
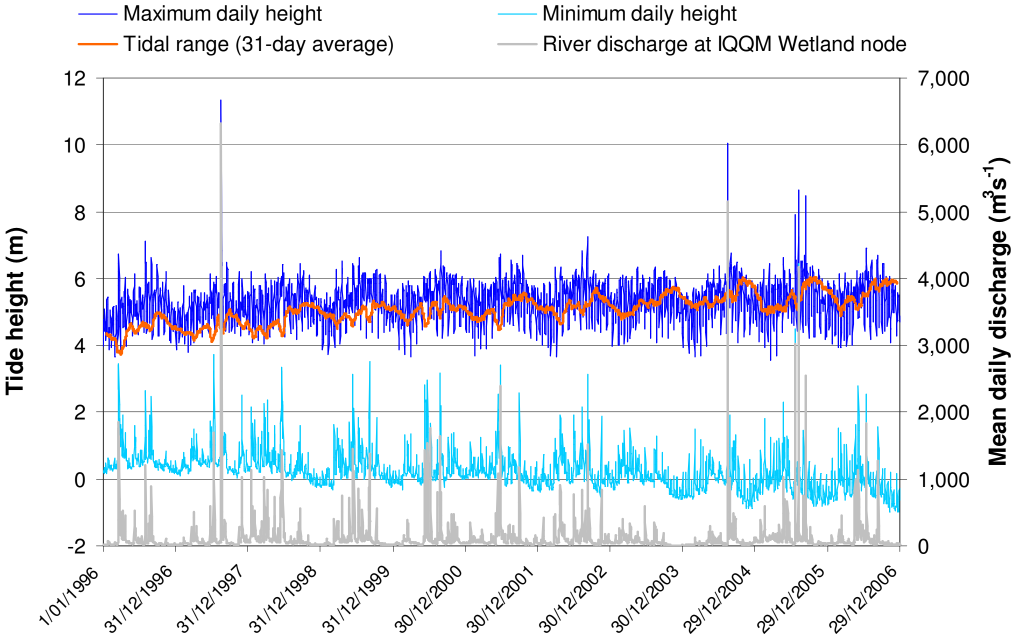


Figure 92: Observed daily tide height extremes and tidal range at Linhai tide gauge from January 1996 to December 2006 and modelled river discharge.



There has been a trend of lowering daily minimum tide levels and increasing maximum tide levels at Linhai chaowei, giving an increasing trend in daily tidal range (Figure 92). The daily minimum tide level in 2006 was more than 1 m lower than it was in 1996. Overall, the tidal range gradually increased over this period by around 1.8 m. This could possibly be related to channel dredging, as tidal propagation in estuaries is very sensitive to water depths over the first several kilometres upstream from the estuary mouth. The trend is not explained by river hydrology as there was no trend of lowering flows over this period. The apparent trend of lower minimum tide levels at Linhai has implications for the biota in Reach 4 and Reach 5. The slack of the low tide is now lower than it once was, exposing a greater area of the channel banks and bed, and lowering depths over the entire bed. This has contracted the area of available habitat. The trend of increasing maximum tide heights means that the upper approx. 0.5 m of the bank that was formerly mostly dry is now mostly wet, which would have altered the vegetation.

A simple hydraulic model was generated by relating the maximum tide heights to river discharge (as predicted for the current model run at the IQQM Wetland node). This relationship demonstrated that peak daily water level in the river at the tide gauge was controlled by the tide for 99.6% of days (Figure 92). However, daily peak river height was significantly related to discharge for discharge greater than approximately 1,500 m^3s^{-1} (Figure 93). The scatter in the relationship is due to the variable effects of tides and the fact that mean daily discharge was used rather than peak discharge (and the ratio of daily peak to daily mean discharge varies between events). This relationship was used to predict the mean daily discharge corresponding the wetland sill level 7.5 ±0.5 m (which allows for uncertainty in the sill level). It can be assumed that on the days when the sill level was exceeded, that the peak daily flow was higher than the mean daily flow. A ratio of peak to mean daily discharge of 1.25 was assumed (based on the observed relationships between peak and mean daily discharge further upstream) to give thresholds for wetland inundation. If it is assumed that 7.5 m is the wetland sill level, then a river stage of 8 m (instantaneous discharge of 3,980 m^3s^{-1}) will inundate it to a depth of 0.5 m (Table 98).

Figure 93: Relationship between daily maximum tide height at Linhai tide gauge and modelled river discharge.

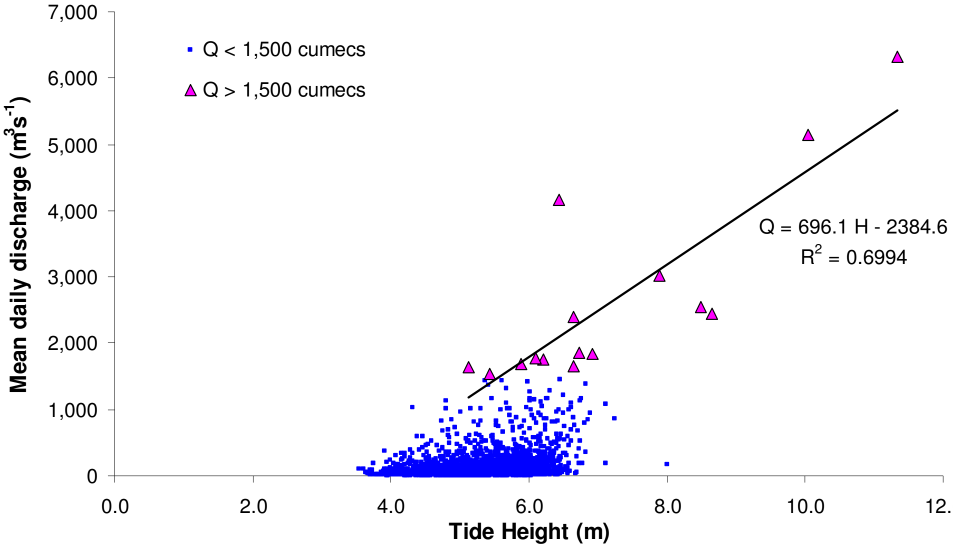


Table 98: Thresholds of inundation for wetland in Reach 4. An elevation of 7.5 m is the sill level, while a river stage of 8 m will inundate it to a depth of 0.5 m.

Wetland inundation sill (m)	Peak daily discharge (m^3s^{-1})	Mean daily discharge (m^3s^{-1})
7.0	3,110	2,488
7.5	3,545	2,836
8.0	3,980	3,184

Chapter 8: Flow Recommendations

This section presents the flow recommendations for each reach. One or more photographs of each reach are provided, together with a table of flow rules for input into the IQQM model. A description of how each flow component relates to the objectives follows. Note that because of the limited information available for each reach there is a high degree of similarity in these descriptions, especially for reaches 1, 2 and 3, which were broadly similar in terms of their physical, and presumably their biological, characteristics.

In order to fully specify the event components, it is necessary to describe them in terms of magnitude, frequency, duration, timing, and rates of change. Magnitude was derived from hydraulics, frequency and duration were derived from the natural frequency and duration, timing was specified as within a pre-determined season, and rate of rise and fall had to be determined from the natural flow series'. Once the magnitudes of events were established, it was possible to determine the maximum allowable and target rates of rise and fall.

8.1 Event rates of rise and fall

Rates of rise and fall were calculated for the flow Pulses, Bankfull and Overbank events for each relevant reach (Reaches 1 – 4). First, the components were separated from the record. This was done, for each component, by selecting all flows equal to the magnitude of the flow component ±20% (the results were relatively insensitive to the width of this band). Then, for each flow component the rises and falls associated with all the events identified in the record were separated, and descriptive statistics calculated for each.

The maximum allowable rate of rise and fall was described by the 5th percentile rate, rather than the maximum observed rate (which, representing only a single observation in the record, is not statistically useful). The median values were calculated as an index of the normal target rates of rise and fall.

For every flow component (e.g. Bankfull) the flow could allowably rise from the magnitude of the flow component below it (e.g. High Flow Pulse) to the magnitude of the flow component in just one day. However, the target rate of rise was 2 days for most of the Pulses. The target rise for Bankfull and Overbank remained at 1 day except in the case of Bankfull for Reach 3. In general, rates of fall were lower than rates of rise, but they were still relatively fast. Maximum allowable rates of fall for Pulses were 1 – 2 days, and 1 day for Bankfull and Overbank. Target rates of fall for Pulses were 2 – 3 days, and 1 – 2 days for Bankfull and Overbank. This analysis highlights the very flashy nature of the pulses and flood events in this stream system.

Table 99: Statistics describing rates of rise and fall associated with the event flow components (calculated from the current flow series'). The rise and fall durations were calculated assuming a rise from the magnitude of the flow component below it. Durations rounded to nearest day.

Component and rise/fall statistic	Reach 1	Reach 2	Reach 3	Reach 4
Low Flow Pulse				
5th%-ile rise (m^3s^{-1})	20	52	78	-
Median rise (m^3s^{-1})	13	29	38	-
Max. rise duration (days)	1	1	1	-
Median rise duration (days)	2	2	2	-
5th%-ile fall (m^3s^{-1})	-14	-37	-45	
Median fall (m^3s^{-1})	-10	-23	-25	-
Max. fall duration (days)	1	1	2	
Median fall duration (days)	2	2	3	-
High Flow Pulse				
5th%-ile rise (m^3s^{-1})	20	52	120	-
Median rise (m^3s^{-1})	13	29	61	-
Max. rise duration (days)	1	1	1	-
Median rise duration (days)	1	2	2	-
5th%-ile fall (m^3s^{-1})	-14	-37	-80	
Median fall (m^3s^{-1})	-10	-23	-47	-
Max. fall duration (days)	1	1	2	
Median fall duration (days)	2	2	3	-
Bankfull				
5th%-ile rise (m^3s^{-1})	190	437	809	5,171
Median rise (m^3s^{-1})	150	294	453	3,674
Max. rise duration (days)	1	1	1	1
Median rise duration (days)	1	1	2	1
5th%-ile fall (m^3s^{-1})	-165	-382	-801	-4,481
Median fall (m^3s^{-1})	-134	-285	-499	-2,963
Max. fall duration (days)	1	1	1	1
Median fall duration (days)	1	1	2	1
Overbank				
5th%-ile rise (m^3s^{-1})	200	440	-	-
Median rise (m^3s^{-1})	158	323	-	-
Max. rise duration (days)	1	1	-	-
Median rise duration (days)	1	1	-	-
5th%-ile fall (m^3s^{-1})	-182	-387	-	-
Median fall (m^3s^{-1})	-141	-340	-	-
Max. fall duration (days)	1	1	-	-
Median fall duration (days)	1	1	-	-

8.2 Reach 1: Zhuxi between the dam site and the first major downstream tributary

Site at the upper section of Reach 1 looking downstream (L) and upstream (R).

Table 100: Summary of flow requirements for Reach 1.

Flow component	Timing	Months	Q_{PEAK} m^3s^{-1}	Q_{DAILY} m^3s^{-1}	Frequency (per year)	Duration	Rise/fall target(max) m^3s^{-1}‡	Indices
Low flow	Low flow season	Oct-Mar	0.5	0.5	continuous or less than if natural			3a, 3b: 75th%-ile
High flow	High flow season	April-Sep	1.3	1.3	continuous or less than if natural			3e; 75th%-ile
Low flow pulse	Low flow season	Oct-Dec; Jan-Mar	20	20	2	1 day in Oct-Dec and 1 day in Jan-Mar	+13(+20)/ -10(-14)	1b 2a 3c, 3d
High flow pulse	Spawning period	April	20	20	1	2 consecutive days	+13(+20)/ -10(-14)	1b 2a 3d, 3f
High flow pulse	High flow season	May-Sep	20	20	4	2 consecutive days	+13(+20)/ -10(-14)	3f
Bankfull†	high flow season	anytime	524	177	0.52	1 d peak; Achieve Q_{PEAK} and Q_{DAILY} on day of peak	+150(+190) / -134(-165)	1a, 1c, 1d 2c
Overbank	High flow season	anytime	571	191	0.52	1 d peak; Achieve Q_{PEAK} and Q_{DAILY} on day of peak	+158(+200) / -141(-182)	2b, 2d

† If Overbank delivered then Bankfull component can be omitted.

‡ Rate is maximum change in discharge that is allowed from one day to the next. Target is recommended rate change, but maximum can be used (at higher environmental risk). If allowable rate change exceeds the required event magnitude then discharge can be raised to the event magnitude over one day.

8.2.1 Cease-to-flow

Not recommended and unlikely to occur naturally. Acceptable in the future if natural occurrence, although prolonged events may have adverse effects on fish, invertebrates and water quality in Zhuxi.

8.2.2 Low Flow

A dry season (Oct-Mar) base-flow of 0.5 m^3s^{-1} is recommended to maintain adequate minimum water depths in riffle habitats and sufficient wetted area and depths in pools and shallow runs (3a and 3b). Water depth in pools should be adequately maintained by the presence of riffles acting as a downstream control on depths. Lower flows are acceptable whenever they would occur naturally (i.e. when inflows to the reservoir fall below 0.5 m^3s^{-1}). The threshold of 0.5 m^3s^{-1} was derived from the hydraulic model to achieve 0.2 m depth over riffles. However, the model is not reliable at these low depths, so the alternative hydrological index was also used. Over the Oct-Mar season the 75th percentile flow was 0.55 m^3s^{-1}. Given that these two estimates were so close, the hydraulically determined value was adopted.

8.2.3 Low Flow Pulse

Periodic flow pulses of 20 m^3s^{-1} have been recommended to flush fine sediments and algae from interstitial spaces and the surfaces of cobbles (3d) and to maintain water quality by 'turning over' pools and re-oxygenating the hyporheic zone. The flushing of fine sediments (1b) (only partially achieved) and the scouring of vegetation from bars (2a) are the controlling objectives for this flow. These flow pulses also provide opportunities for fish to move between pools (3c) that might otherwise be isolated by shallow water over riffles during low flows and mobilise terrestrial organic material thereby providing a potentially important source of carbon for aquatic food webs (2a). Two such events have been recommended, each lasting a minimum of 1 day.

8.2.4 High Flow

A wet season (Apr-Sep) baseflow of 1.3 $m^3s^{-1}y$ is recommended to maintain sufficient water depths for fish movement into and out of spawning areas (3e), and to ensure that average flow velocities in the channel exceed 0.25 ms^{-1} (3e), which is necessary to maintain the neutrally buoyant and drifting eggs or grass carp, silver carp and black carp in the water column (Tang, 1989; Zhong, 1996). The high baseflow will also ensure sufficient backwater habitats exist for juvenile and young of the year fish (3a and 3b). The threshold of 1.3 m^3s^{-1} was derived from the hydraulic model to achieve velocity >0.15 – 0.25 ms^{-1} over riffles. However, the model is not reliable at these low velocities, so the alternative hydrological index was also used. Over the Apr-Sep season the 75th percentile flow was 1.2 m^3s^{-1}. Given that these two estimates were so close, the hydraulically determined value was adopted.

8.2.5 High Flow Pulse

Periodic flow pulses of 20 m^3s^{-1} have been recommended to flush fine sediments and algae from interstitial spaces and the surfaces of cobbles respectively (1b, 3d) and to maintain water quality by 'turning over' pools and re-oxygenating the hyporheic zone (3d). The mobilisation of fine sediments and the scouring of vegetation from bars are the controlling objectives for this flow. An event has been specifically recommended during April to coincide with the onset of spawning by several carp species – both to potentially stimulate spawning and to provide opportunities for upstream migration (3f). An additional 4 events are necessary in the period May-September to scour detritus and algae from the streambed (1b, 3d) and vegetation from bars (2a). Releases can coincide with natural increases in discharge downstream to reduce the volume of water released from the dam. Each high flow pulse should be of 2 days minimum duration.

8.2.6 Bankfull Flow

Zhuxi is a typical gravel bed river in which many of the natural channel features (pools, riffles, bars) are maintained by bankfull flows mobilising bed material (1a, 1c, 1d) and scouring encroaching terrestrial vegetation (2a, 2c). These geomorphic features create unique habitats that must be maintained to meet the fish and vegetation objectives. The peak discharge required to reach the top of the bank at the surveyed cross-section was estimated to be 524 m^3s^{-1}, but this need only be reached instantaneously. The associated mean daily flow for input to the IQQM model is 177 m^3s^{-1}. These flows should on average occur once every 2 years.

8.2.7 Overbank Flow

Overbank flows have been recommended to maintain the natural disturbance regime in riparian areas, where periodic floods can play a key role in structuring the vegetation (2b), including wetland communities (2d). Flows necessary to inundate riparian areas in close proximity to the channel were estimated at 571 m^3s^{-1} (instantaneous), or 191 m^3s^{-1} (for daily flow for IQQM input). Overbank flows are less likely to be important for fish in reach 1 due to the absence of extensive floodplain areas. In reach 1 overbank flows should on average occur once every 2 years.

8.3 Reach 2: Zhuxi between the first major tributary below the dam site and the downstream confluence with Yong'anxi

Site in the mid-section of Reach 2 looking upstream before (L) and after (R) flooding

Hyporheic flow emerging from the streambank (L); riparian vegetation (R) in Reach 2

8.3.1 Cease-to-flow

Not recommended and unlikely to occur naturally. Acceptable in the future if natural occurrence, although prolonged events may have adverse effects on fish, invertebrates and water quality in Zhuxi.

Table 101: Summary of flow requirements for Reach 2.

Flow component	Timing	Months	Q_{PEAK} m^3s^{-1}	Q_{DAILY} m^3s^{-1}	Frequency (per year)	Duration	Rise/fall max.(target) m^3s^{-1}‡	Indices
Low flow	Low flow season	Oct-Jan	1.3	1.3	continuous or less than if natural			3a, 3b 75th%-ile
Low flow	Low flow season	Feb-Mar	3.4	3.4	continuous or less than if natural			3a, 3b 75th%-ile
High flow	High flow season	April-Sep	4.0	4.0	continuous or less than if natural			3e 75th%-ile
Low flow pulse	Low flow season	Oct-Dec; Jan-Mar	53	53	2	2 consecutive days in Oct-Dec and 2 days in Jan-Mar	+29(+52)/ -23(-37)	1b 3c, 3d
High flow pulse	Spawning period	April	53	53	1	2 consecutive days	+29(+52)/ -23(-37)/	2a 3f
High flow pulse	High flow season	May-Sep	53	53	4	2 consecutive days	+29(+52)/ -23(-37)/	3f
Bankfull†	anytime	anytime	1,011	397	0.58	1 d peak; Achieve Q_{PEAK} and Q_{DAILY} on day of peak	+294(+437)/ -285(-382)	1a, 1b, 1c 3c
Overbank	High flow season	April-Sep	1,102	428	0.58	1 d peak; Achieve Q_{PEAK} and Q_{DAILY} on day of peak	+323(+440)/ -340(-387)	2b, 2d 3g

† If Overbank delivered then Bankfull component can be omitted.

‡ Rate is maximum change in discharge that is allowed from one day to the next. Target is recommended rate change, but maximum can be used (at higher environmental risk). If allowable rate change exceeds the required event magnitude then discharge can be raised to the event magnitude over one day.

8.3.2 Low Flow

Due to marked seasonal variation in natural low flows over the dry season, a separate low flow has been specified for Oct-Jan (1.3 m^3s^{-1}) and Feb-Mar (3.4 m^3s^{-1}). These thresholds are based on the 75th flow percentile values for those periods, as the cross-section for this reach was not conducive to good model performance at low depths. These flows should both be sufficient to maintain adequate minimum water depths in riffle habitats (3b) and sufficient wetted area and depths in pools and shallow runs (3a). Water depth in pools should be adequately maintained by the presence of riffles acting as a downstream control on depths. The higher flow for Feb-Mar ensures that the recommended regime remains within the historical range. Lower flows are acceptable whenever they would occur naturally.

8.3.3 Low flow Pulse

Periodic flow pulses of 53 m^3s^{-1} are recommended to flush fine sediments and algae from interstitial spaces and the surfaces of cobbles (1b, 3d) and to maintain water quality by 'turning over' pools and re-oxygenating the hyporheic zone. The mobilisation of sediment (1b) and the scouring of vegetation from bars (2a) are the controlling objectives for this flow. These flow pulses also provide opportunities for fish to move between pools (3c) that might otherwise be isolated by shallow water over riffles during low flows and mobilise terrestrial organic material thereby providing a potentially important source of carbon for aquatic food webs (2a). Two such events (1 Oct-Dec and 1 Jan-Mar), each lasting 2 consecutive days, are recommended to reflect the natural frequency of these events.

8.3.4 High Flow

A wet season (Apr-Sep) baseflow of 4 m^3s^{-1} is recommended to maintain sufficient water depths for fish movement into and out of spawning areas (3e), and to ensure that average flow velocities in the channel exceed 0.25 ms^{-1} (3e), which is necessary to maintain the neutrally buoyant and drifting eggs or grass carp, silver carp and black carp in the water column (Tang, 1989; Zhong, 1996). The high baseflow will also ensure sufficient backwater habitats exist for juvenile and young of the year fish (3a and 3b). The estimate of 4 m^3s^{-1} should be regarded as uncertain because the performance of the hydraulic model is poor at low depths and discharges. The 75th percentile flow for Apr-Sep was 3.6 m^3s^{-1} and for the shorter Apr-Jul period it was 4.0 m^3s^{-1}. Given the proximity of these estimates for the High Flow component the higher, more conservative, value of 4.0 m^3s^{-1} was adopted.

8.3.5 High Flow Pulse

Periodic flow pulses of 53 m^3s^{-1} have been recommended to flush fine sediments and algae from interstitial spaces and the surfaces of cobbles respectively (1b, 3d) and to maintain water quality by ‘turning over’ pools and re-oxygenating the hyporheic zone (3d). The mobilisation of sediments and the scouring of vegetation from bars are the controlling objectives for this flow. An event has been specifically recommended during April to coincide with the onset of spawning by several carp species – both to potentially stimulate spawning and to provide opportunities for upstream migration (3f). An additional 4 events are necessary in the period May-October to scour detritus and algae from the streambed (3d) and vegetation from bars (2a). Releases can coincide with natural increases in discharge downstream to reduce the volume of water released from the dam. Each high flow pulse should be of 2 days minimum duration.

8.3.6 Bankfull Flow

Zhuxi is a typical gravel bed river in which many of the natural channel features (pools, riffles, bars) are maintained by bankfull flows mobilising bed material (1a, 1c, 1d) and scouring encroaching terrestrial vegetation (2a, 2c). These geomorphic features create unique habitats that must be maintained to meet the fish and vegetation objectives. The peak discharge required to reach the top of the bank at the surveyed cross-section is estimated to be 1,011 m^3s^{-1}, but this need only be reached instantaneously. The associated mean daily flow for inclusion in the IQQM model is 397 m^3s^{-}. These flows should on average occur approximately once every 2 years.

8.3.7 Overbank flows

Overbank flows have been recommended to maintain the natural disturbance regime in riparian areas, where periodic floods can play a key role in structuring the vegetation (2b), including wetland communities (2d). Flows necessary to inundate riparian areas in close proximity to the channel were estimated at 1,102 m^3s^{-1} (instantaneous), or 428 m^3s^{-1} (daily flow for IQQM input). Overbank flows may also play a role in allowing fish to access floodplain habitats in the lower reaches of Zhuxi where a more extensive floodplain occurs (3g). In reach 2 overbank flows should on average occur just over once every 2 years.

8.4 Reach 3: Yong’anxi between the Zhuxi confluence and Shifengxi confluence

Site on Yong’anxi at junction of Zhuxi, looking upstream during high flow post Typhoon event (L); fish buried in stones on bars during the previous recent flood (R)

Table 102: Summary of flow requirements for Reach 3.

Flow component	Timing	Months	Q_{PEAK} m^3s^{-1}	Q_{DAILY} m^3s^{-1}	Frequency (per year)	Duration	Rise/fall max.(target) m^3s^{-1}‡	Indices
Low flow	Low flow season	Oct-Jan	6.8	6.8	continuous or less than if natural			3a, 3b 75th%-ile
Low flow	Low flow season	Feb-Mar	17.3	17.3	continuous or less than if natural			3a, 3b 75th%-ile
High flow	High flow season	April-Sep	22.2	22.2	continuous or less than if natural			3e 75th%-ile
Low flow pulse	Low flow season	Oct-Mar	96	96	4	4 consecutive days	+38(+78)/ -25(-45)	1b 3c, 3d
High flow pulse	High flow season	April-Sep	146	146	6	7 consecutive days	+61(+120)/ -47(-80)	2a 3f, 3g
Bankfull	anytime	anytime	1,289	948	1.3	1 d peak; achieve Q_{PEAK} and Q_{DAILY} on day of peak	+453(+809)/ -499(-801)	1a, 1b, 1c 2c
Overbank					None specified			

‡ Rate is maximum change in discharge that is allowed from one day to the next. Target is recommended rate change, but maximum can be used (at higher environmental risk). If allowable rate change exceeds the required event magnitude then discharge can be raised to the event magnitude over one day.

8.4.1 Cease-to-flow

Not recommended and unlikely to occur naturally. Acceptable in the future if natural occurrence, although prolonged events may have adverse effects on fish, invertebrates and water quality in Yong’anxi.

8.4.2 Low Flow

Due to marked seasonal variation in natural low flows over the dry season, a separate low flow has been specified for Oct-Jan (6.8 m^3s^{-1}) and Feb-Mar (17.3 m^3s^{-1}). Empirical surveys of the channel cross-section were not conducted in this reach, so a project-derived hydraulic model was not available for this reach.

However, a stream flow gauge was located just at the downstream end of the reach. A hydraulic model was derived on the basis of a cross section from the gauge, combined with the gauge rating curve. At cease to flow there was 1.74 m depth of water at the cross-section, suggesting that the control for the gauge was further downstream. Thus, this hydraulic relationship could not be used to specify low flows. As an alternative, the low flow thresholds were set equivalent to the flow exceeded 75% of the time for the defined season. This reflects the low end of the normal baseflow range.

The expectation is that these flows will maintain adequate minimum water depths in riffle habitats (3b) and sufficient wetted area and depths in pools and shallow runs (3a). Note that these riffle and pool habitats were not observed in the field (as this reach was in flood at the time of inspection), but exposed bed material was visible on the satellite image, and the reach is sufficiently high gradient to have pool/riffle morphology. Water depth in pools should be adequately maintained by the presence of riffles acting as a downstream control on depths. The higher flow for Feb-Mar ensures that the recommended regime remains within the historical range. Lower flows are acceptable whenever they would occur naturally. Note that in this section of Yong'anxi low flows will reflect overall levels of water extraction from the entire upstream catchment, not just diversions from Zhuxi.

8.4.3 Low flow Pulse

The low flow pulse component was assumed to correspond to inundation of the lower Bench I (Figure 91). Periodic flow pulses of 96 $m^3s^{-1}$are recommended to flush fine sediments and algae from interstitial spaces and the surfaces of cobbles (1b, 3d) and to maintain water quality by 'turning over' pools and re-oxygenating the hyporheic zone. The mobilisation of sediment (1b) and the scouring of vegetation from bars (2a) are the controlling objectives for this flow. These flow pulses also provide opportunities for fish to move between pools (3c) that might otherwise be isolated by shallow water over riffles during low flows and mobilise terrestrial organic material thereby providing a potentially important source of carbon for aquatic food webs (2a). These events should occur approximately 4 times each year during the period October-March (natural frequency), and each event should last 4 consecutive days (natural median duration).

8.4.4 High Flow

At cease to flow there was 1.74 m depth of water at the gauge cross-section, suggesting that the control for the gauge was further downstream. Thus, the hydraulic relationship for this reach could not be used to specify low flows. As an alternative, the high flow thresholds was set equivalent to the flow exceeded 75% of the time for the defined season. This reflects the low end of the normal baseflow range. The 75th percentile flow for the entire Apr-Sep period was 20.7 m^3s^{-1} and for the shorter Apr-Jul period it was 22.2 m^3s^{-1}. The higher, more conservative, value of 22.2 m^3s^{-1} is recommended to maintain sufficient water depths for fish movement into and out of spawning areas (3e). The high baseflow will also ensure sufficient backwater habitats exist for juvenile and young of the year fish (3a and 3b). Note that in this section of Yong'anxi high flows will reflect overall levels of water extraction from the entire upstream catchment, not just diversions from Zhuxi.

8.4.5 High Flow Pulse

The low flow pulse component was assumed to correspond to inundation of the middle Bench II (Figure 91). Periodic flow pulses of 146 m^3s^{-1} are recommended to periodically flush fine sediments and algae from interstitial spaces and the surfaces of cobbles respectively (1b, 3d) and to maintain water quality by 'turning over' pools and re-oxygenating the hyporheic zone (3d). The mobilisation of sediments (1b) and the scouring of vegetation from bars (2a) are the controlling objectives for this flow. High flow pulses should occur 6 times annually (natural frequency) during the period April-September, with each event lasting 7 consecutive days (natural median duration).

8.4.6 Bankfull Flow

Like Zhuxi, Yong'anxi is a typical gravel bed river in which many of the natural channel features (pools, riffles, bars) are maintained by bankfull flows mobilising bed material (1a, 1c, 1d) and scouring encroaching terrestrial vegetation (2a, 2c). These geomorphic features create unique habitats that must be maintained to meet the fish and vegetation objectives. The peak discharge required to reach the top of the bank at the gauge cross-section is 1,289 m^3s^{-1} (Figure 91), but this need only be reached instantaneously. The associated mean daily flow for inclusion in the IQQM model is 948 m^3s^{-1}. These flows should on average occur 1.3 times per year, or 4 events every 3 years (based on natural frequency of occurrence).

8.4.7 Overbank flows

Overbank flows were not recommended for this reach due to the presence of extensive levee banks that limit the potential benefits of overbank flows.

8.5 Reach 4: The freshwater estuarine section of Lingjiang from Shifengxi confluence to downstream of Linhai city

Floodplain inundation at Ling Lake (L); the wetland site upstream of Linhai city (R). Photos taken on 12/10/2007, the week following a major inundation event. Note thick layer of silt deposited at both locations.

8.5.1 Low Flow

Due to marked seasonal variation in natural low flows over the dry season, a separate low flow has been specified for Oct-Jan (16.0 m^3s^{-1}) and Feb-Mar (31.8 m^3s^{-1}). Lower flows are acceptable whenever they would occur naturally. The low flow thresholds were not based on hydraulic criteria (due to lack of information), but were equivalent to the flow exceeded 75% of the time for the defined season. This reflects the low end of the normal baseflow range. It is expected that this flow will maintain low salinity flowing water on the ebb tide in the upper part of the reach (helping to maintain the position of the fresh/brackish/saline interface), otherwise this flow component does not have a strong ecological role. Note that in this section of Lingjiang, low flows will reflect overall levels of water extraction from the entire upstream catchment, not just diversions from Zhuxi.

Table 103: Summary of flow requirements for Reach 4.

Flow component	Timing	Months	Q_{PEAK} m^{3}s^{-1}	Q_{DAILY} m^{3}s^{-1}	Frequency (per year)	Duration	Rise/fall max.(target) m^{3}s^{-1}‡	Comment	Indices
Low flow	Low flow season	Oct-Jan	16.0	16.0	continuous or less than if natural			Will maintain low salinity flow on the ebb tide in the upper part of the reach	3h, 3i, 3j 75th%-ile
Low flow	Low flow season	Feb-Mar	31.8	31.8	continuous or less than if natural				3h, 3i, 3j 75th%-ile
High flow	High flow season	April-Sep	46.0	46.0	continuous or less than if natural				3h, 3i, 3j 75th%-ile
Low flow pulse	None specified. Pulses will not influence water level; a minor and temporary influence on downstream salinity gradient is possible but cannot be linked to known ecological processes								
High flow pulse									
Bankfull†	anytime	anytime	3,110	2,488	0.59*	1 d	+3,674(+5,171)/ -2,963(-4,481)	Event to reach 7.0 m at wetland	1a, 1c, 1d 2b, 2d 3g, 3i, 3j
Bankfull†	anytime	anytime	3,545	2,836	0.48*	1 d	+3,674(+5,171)/ -2,963(-4,481)	Event to reach 7.5 m at wetland	
Bankfull†	anytime	anytime	3,980	3,184	0.45*	1 d	+3,674(+5,171)/ -2,963(-4,481)	Event to reach 8.0 m at wetland	
Overbank	None specified								

† Due to uncertainty in the stage required to inundate the wetland in this reach, three scenarios spanning 7.0 - 8.0 m have been identified. Only one of these events needs to be implemented. The higher level is preferred to ensure full inundation of the wetland, provided this can be achieved with minimal additional impacts on security of supply over the lower scenarios. Duration is 1 day at peak, and to achieve Q_{PEAK} and Q_{DAILY} on day of peak.

‡ Rate is maximum change in discharge that is allowed from one day to the next. Target is recommended rate change, but maximum can be used (at higher environmental risk). If allowable rate change exceeds the required event magnitude then discharge can be raised to the event magnitude over one day.

* Probability (P) of exceedance in current flow series (ARI = 1/P).

8.5.2 High Flow

A wet season (Apr-Sep) baseflow of 46.0 m^{3}s^{-1} is recommended to maintain low salinity flowing water on the ebb tide in the upper part of the reach (helping to maintain the position of the fresh/brackish/saline interface), otherwise this flow component does not have a strong ecological role. Lower flows are acceptable whenever they would occur naturally. The low flow threshold was not based on hydraulic criteria (due to lack of information), but was equivalent to the flow exceeded 75% of the time for the defined season. This reflects the low end of the normal baseflow range. Note that in this section of Lingjiang, low flows will reflect overall levels of water extraction from the entire upstream catchment, not just diversions from Zhuxi.

8.5.3 Pulses

A convincing ecological basis for pulses could not be established in this reach. Pulses will not influence water level, but may have a minor and temporary influence on downstream salinity gradient.

8.5.4 Bankfull Flow

The upper limit of Reach 4 defines the approximate upstream extent of significant tidal influence in Lingjiang, whilst the downstream limit (just below Linhai city) defines the upstream extent of saline water intrusion. As a result of the tidal influence, hydraulic conditions within the river are controlled more by tidal processes than inflows from upper reaches. The exception is under high flow conditions (Figure 2a and 2b). As water levels are controlled by river discharge only during high flow events, recommendations have been made only for Bankfull flows, primarily to maintain periodic inundation of and access to an important riparian wetland area (2d). To this end, these Bankfull recommendations also address the Overbank flows recommendation for fish (3g). A separate Overbank flow component was not specified due to the widespread floodplain levees in this Reach. The potential impacts of reduced low flows on upstream intrusion of saline water is covered as part of the risk assessment for Reach 5.

For Reach 4 the estimated flows required to achieve Bankfull and inundate the fringing wetland areas range between 3,110 m^3s^{-1} (instantaneous) and 3,980 m^3s^{-1} (instantaneous). This uncertainty is due to the lack of a detailed survey of the bank height adjacent to the wetland to accurately determine the sill level. Monitoring of the flows required to inundate the wetland could quickly address this uncertainty. The frequency of these events ranges between 0.45 - 0.59 times per year (i.e. about once every 2 years).

8.5.5 Overbank flows

Overbank flows were not recommended for this reach as the bankfull component achieves inundation of the important ecological asset (wetland).

8.6 Reach 5 and Reach 6: The saltwater estuarine section of Lingjiang/Jiaojiang

Mudflats at the mouth of the estuary in Reach 6

Due to lack of resources, it was not possible to derive specific flow rules for Reach 5 and Reach 6 using the hydraulic-based methodology used in the other reaches. The hydrodynamics of the estuary are complex, and derivation of flows based on an understanding of the hydrodynamics would require a separate investigation. Interestingly, the hydraulics of the Jiaojiang estuary have been very well studied, and there is an existing hydrodynamic model, so the tools to conduct such an estuarine environmental flows investigation are available.

For Reaches 5 and 6, a risk assessment was undertaken to explore the potential impacts associated with the following key hydrological change indices:

i. Reduction in summer baseflow
ii. Reduction in winter baseflow
iii. Reduction in the frequency of bankfull floods

While the open Jiaojiang estuary is dominated by marine influences, freshwater flows are also ecologically important. During high river flow events the saline estuarine water is pushed out to sea. This causes a major disruption to the normal ebb and flow cycle; the biota have evolved to either take advantage of this sudden and perhaps persistent change in the hydraulics and salinity regime, or to minimise negative impacts. A significant reduction in the frequency of major runoff events, or similarly, a significant reduction in the volume of water passing to the estuary during major rainfall events could have significant ecological consequences. Baseflows determine the longitudinal position of the salinity gradient during non-flood times. Weaker baseflows allow saline water to penetrate further upstream.

The degree of hydrological change in the Lingjiang-Jiaojiang estuary is analysed in the following section of this report. In this section the results of that analysis are used in a risk assessment.

For each of these hydrological changes, a list was made of the ecological assets that were potentially at risk of impairment from such a change (Table 104). The assets were rated according to three conservation status classes, with the consequence of change (consequence) being higher the higher the conservation status (Table 105). Degree of change (likelihood of impairment due to hydrological change) was ranked into 4 classes (Table 106). The product of consequence and likelihood gives risk of impairment, which was grouped into 5 classes, ranging from insignificant to very high (Table 106).

Consequence and likelihood scores were assigned to each ecological asset, and risk scores were calculated for each asset for five future scenarios for Reach 5 (Table 107) and Reach 6 (Table 108):

i. R0E0, Zhuxi 2020 with Shisandukeng water transfers
ii. R0E1, Zhuxi 2020 with Shisandukeng water transfers plus Environmental Flow Rules
iii. R1E0, Zhuxi 2020 with Shisandukeng water transfers plus Modified Changtan Operation Rule (Reduce valve operating storage)
iv. R1E1, Zhuxi 2020 with Shisandukeng water transfers plus Environmental Flow Requirements plus Modified Changtan Operating Rule (Reduced valve operating storage level)
v. R2E0, Zhuxi 2020 with Shisandukeng water transfers plus Dam on the Yong’anxi system upstream of Zhuxi

Table 104: Main hydrological and resultant physical and ecological changes likely due to reduction in freshwater inflows into Lingjiang/Jiaojiang estuary.

Key hydrological change index	Potential environmental changes	Ecological asset potentially at risk of impairment	ASSET CODE
Reduction in Oct-Mar baseflow	‣ Upstream migration of salt wedge ‣ Increased sediment influx from the Yangtze River (Changjang) ‣ Increased salinity within near-shore environments ‣ Reduced depths in the river channel due to sedimentation ‣ Altered biogeochemical cycling	Upstream migration of anadromous fish (e.g. Plecoglossus, Macrura reversii, Coilia ectenes, Coilia mystus)	1A
		Marine derived freshwater opportunists (Lateolabrax japonicus)	1B
		Estuarine resident fish (e.g. Large Yellow Croaker, Acanthopagrus schlegel)	1C
		Species inhabiting tidal mudflats (e.g. Crabs, Blue-spotted mudskipper, shellfish)	1D
		Freshwater dependent vegetation (e.g. fringing reed beds and low lying forests)	1E
Reduction in April-Sep baseflow	‣ Upstream migration of salt wedge ‣ Increased sediment influx from the Yangtze River (Changjang) ‣ Increased salinity within near-shore environments ‣ Reduced depths in the river channel due to sedimentation ‣ Altered biogeochemical cycling	Upstream migration of anadromous fish (e.g. Plecoglossus, Macrura reversii, Coilia ectenes, Coilia mystus)	2A
		Marine derived freshwater opportunists (Lateolabrax japonicus)	2B
		Estuarine resident fish (e.g. Large Yellow Croaker, Acanthopagrus schlegel)	2C
		Species inhabiting tidal mudflats (e.g. Crabs, Blue-spotted mudskipper)	2D
		Freshwater dependent vegetation (e.g. fringing reed beds and low lying forests)	2E
Reduction in flood magnitude and frequency	‣ Upstream migration of salt wedge ‣ Increased sediment influx from the Yangtze River (Changjang) ‣ Increased salinity within near-shore environments ‣ Reduced depths in the river channel due to sedimentation ‣ Altered biogeochemical cycling	Upstream migration of anadromous fish (e.g. Plecoglossus, Macrura reversii, Coilia ectenes, Coilia mystus)	3A
		Marine derived freshwater opportunists (Lateolabrax japonicus)	3B
		Estuarine resident fish (e.g. Large Yellow Croaker, Acanthopagrus schlegel)	3C
		Species inhabiting tidal mudflats (e.g. Crabs, Blue-spotted mudskipper)	3D
		Freshwater dependent vegetation (e.g. fringing reed beds and low lying forests)	3E

Table 105: Three key classes of ecological assets, and score for consequence to ecosystem if a change occurs. Also, score for likelihood of impairment due to hydrological change corresponding to four degrees of change.

Asset	Consequence score
Species of commercial or national conservation significance	3
Species of recreational or regional conservation significance	2
Native spp. with no particular commercial, recreational or conservation status	1
Degree of change	**Likelihood score**
No significant change in quality or extent of habitat / process	0
Minor change in quality or extent of habitat / process	1
Major change in quality or extent of habitat / process	2
Loss of habitat or process	3

Table 106: Risk matrix, showing classes of risk of impairment for product of consequence and likelihood scores.

		Likelihood			
		0	1	2	3
Consequence	1	very low	low	moderate	moderate
	2	very low	moderate	high	high
	3	very low	moderate	high	very high

Table 107: Risk of impairment to three key classes of ecological assets in Reach 5 (Lingjiang section of estuary) in response to hydrological changes associated with five alternate future scenarios of reservoir construction and operation. L = Likelihood, R = Risk. Future scenarios explained in text.

Future scenario			1		2		3		4		5	
Index	Asset code	Con-sequence	L	R	L	R	L	R	L	R	L	R
Reduction in Low Flow baseflow			8-10%		5-7%		8-10%		6-7%		9-11%	
	1A	3	1	3	1	3	1	3	1	3	1	3
	1B	2	0	0	0	0	0	0	0	0	0	0
	1C	3	0	0	0	0	0	0	0	0	0	0
	1D	3	0	0	0	0	0	0	0	0	0	0
	1E	1	0	0	0	0	0	0	0	0	0	0
Reduction in High Fflow baseflow			4-9%		3-7%		4-9%		3-7%		4-10%	
	2A	3	1	3	1	3	1	3	1	3	1	3
	2B	2	0	0	0	0	0	0	0	0	0	0
	2C	3	1	3	1	3	1	3	1	3	1	3
	2D	3	0	0	0	0	0	0	0	0	0	0
	2E	1	0	0	0	0	0	0	0	0	0	0
Reduction in flood magnitude and frequency			14%		7%		14%		7%		14%	
	3A	3	1	3	0	0	1	3	0	0	1	3
	3B	2	0	0	0	0	0	0	0	0	0	0
	3C	3	0	0	0	0	0	0	0	0	0	0
	3D	3	0	0	0	0	0	0	0	0	0	0
	3E	1	1	1	0	0	1	1	0	0	1	1

Table 108: Risk of impairment to three key classes of ecological assets in Reach 6 (Jiaojiang section of estuary) in response to hydrological changes associated with five alternate future scenarios of reservoir construction and operation. L = Likelihood, R = Risk. Future scenarios explained in text.

Future scenario			1		2		3		4		5	
Index	**Asset code**	**Con-sequence**	**L**	**R**	**L**	**R**	**L**	**R**	**L**	**R**	**L**	**R**
			13-17%		11-14%		13-17%		11-15%		13-17%	
Reduction in Low Flow baseflow	1A	3	1	3	1	3	1	3	1	3	1	3
	1B	2	0	0	0	0	0	0	0	0	0	0
	1C	3	0	0	0	0	0	0	0	0	0	0
	1D	3	0	0	0	0	0	0	0	0	0	0
	1E	1	0	0	0	0	0	0	0	0	0	0
			6-8%		5-6%		6-8%		5-6%		6-8%	
Reduction in High Fflow baseflow	2A	3	1	3	1	3	1	3	1	3	1	3
	2B	2	0	0	0	0	0	0	0	0	0	0
	2C	3	1	3	1	3	1	3	1	3	1	3
	2D	3	0	0	0	0	0	0	0	0	0	0
	2E	1	0	0	0	0	0	0	0	0	0	0
			16%		17%		16%		17%		16%	
Reduction in flood magnitude and frequency	3A	3	1	3	1	3	1	3	1	3	1	3
	3B	2	0	0	0	0	0	0	0	0	0	0
	3C	3	0	0	0	0	0	0	0	0	0	0
	3D	3	0	0	0	0	0	0	0	0	0	0
	3E	1	1	1	1	1	1	1	1	1	1	1

The 5 scenarios examined appear to pose a fairly minimal threat to the ecological assets in reaches 5 and 6, with the greatest, yet still only *moderate*, threat being posed to the upstream movement of migratory fish and to estuarine resident fish species. The main threat to the latter group is likely to be a change in the distribution and availability of suitable spawning habitats, which are often located in areas with salinity levels below that of seawater. Reductions in High Flow baseflows during the spawning period may cause changes in salinities in the middle and upper estuary that may isolate appropriate spawning sites in terms of habitat from areas with appropriate water chemistry.

Whilst specific information on *Acanthopagrus Schlegelii* is unavailable, salinity levels are known to influence spawning behaviour in closely related species. For example, a review by Norriss et al. (2002) indicates that *Acanthopgrus butcheri* (Australian Black Bream) spawn in salinities ranging between 8 – 45 ppt, but that spawning is often more successful at intermediate salinities. Floods also play a major role in periodically flushing estuaries and redistributing salinity gradients, and in inundating low lying wetland areas dependent on freshwater. Hence these also were identified as an important component of the flow regime to consider. It is worth noting that in Reach 5, scenarios that included environmental flow rules ameliorated the risks associated with a reduction in flood frequency for asset classes 3A and 3E (migratory fish and freshwater dependent vegetation).

Overall, it would appear that construction of dams on Zhuxi and Yong'anxi would cause small but incremental changes in the baseflow volume and flood magnitude and frequency in reaches 5 and 6. This incremental change highlights the importance of assessing the impacts of water resource development at the basin scale, as further development in other sub-catchments will almost certainly increase the risk posed to ecological assets over the levels reported here.

The following section details how hydrological indices were derived to assess the risk associated with the future management scenarios.

Chapter 9: Hydrological Impacts of Future Management Scenarios

9.1 Baseflows

Baseflows were analysed by examining a single index. The dry period and wet period baseflows recommended as the minimum environmental flows for the reaches corresponded to the flows exceeded 75% of the time. Under a managed regime, flows do not have to exceed this threshold all of the time, with the "or natural" clause meaning that if natural inflows to the reach are lower than the threshold then natural flows apply. In this environmental flows assessment the current regime was considered equivalent to the "natural" scenario, because the dam is yet to be constructed on Zhuxi. However, there are other dams in the Jiaojiang system, so the current flow series for Yong'anxi and further downstream are not "natural".

It would be expected that under the current regime, the "or natural" case will apply on average for 25% of the time. For the two estuarine reaches (Lingjiang and Jiaojiang) the flow thresholds corresponding to the 75th percentile flow were determined for the current flow regime, with a value calculated for the four main defined flow periods. Then the percentages of time that these thresholds were exceeded in the future scenarios were calculated for each of the seasons. The difference in these percentages from 75% represents a deviation from the current baseflow regime. The period of time represented by the difference will experience flows less than the recommended baseflow threshold, while under the current regime the flow would have been at least equal to the threshold.

The baseflow analysis revealed that the high flow April-July and August-September periods suffered greater reduction in baseflows than did the low flow October-January and February-March periods (Table 109). This is probably explained by the water resources development tending to capture water in the high flow periods. Also, the Jiaojiang reach was consistently more affected than Lingjiang in the wet period, while in the dry period there was no difference between the sites (Table 109).

Table 109: Percent of time that the 75th percentile flows under current regime are exceeded under future water resources development scenarios. Future scenarios explained in text.

Scenario	Location	Aug-Sep	Oct-Jan	Feb-Mar	Apr-Jul
		Percent of time that the 75th percentile flows under current are exceeded under future water resources development scenarios			
1. R0E0	Lingjing	65%	66%	71%	67%
	Jiaojiang	58%	67%	69%	62%
2. R0E1	Lingjing	68%	68%	72%	70%
	Jiaojiang	61%	69%	70%	64%
3. R1E0	Lingjing	65%	66%	71%	67%
	Jiaojiang	58%	67%	69%	62%
4. R1E1	Lingjing	68%	68%	72%	69%
	Jiaojiang	60%	69%	70%	64%
5. R2E0	Lingjing	64%	65%	71%	66%
	Jiaojiang	58%	67%	69%	62%
		Reduction from 75% under future water resources development scenarios			
1. R0E0	Lingjing	10%	9%	4%	8%
	Jiaojiang	17%	8%	6%	13%
2. R0E1	Lingjing	7%	7%	3%	5%
	Jiaojiang	14%	6%	5%	11%
3. R1E0	Lingjing	10%	9%	4%	8%
	Jiaojiang	17%	8%	6%	13%
4. R1E1	Lingjing	7%	7%	3%	6%
	Jiaojiang	15%	6%	5%	11%
5. R2E0	Lingjing	11%	10%	4%	9%
	Jiaojiang	17%	8%	6%	13%

9.2 Flood frequency

One way of assessing the impact of water resources development on flood frequency is to plot and compare the partial duration flood frequency curves for the various scenarios. These curves suggest that modelled development scenarios lead to only a modest decline in flood frequency for any given discharge, and the scenarios all have a similar level of impact (Figure 94).

For Reach 4, the estimated flows required to achieve bankfull and inundate the fringing wetland areas ranged between 2,488 m^3s^{-1} and 3,184 m^3s^{-1} when measured as mean daily flows. The highest of these thresholds occurred with an average recurrence interval of 2.2 years, or a probability of exceedance of 0.45. For the purposes of assessing the impact of water resources development on flood frequency, it is assumed that this event represents the bankfull discharge for the upper end of the estuary, and that the event occurring with a probability of exceedance of 0.45 at the end of system represents the bankfull discharge there. At the end of system IQQM reporting node the equivalent discharge is 4,040 m^3s^{-1}.

For the future scenarios, for Reach 5, the probability of exceedance of the bankfull event declines by either 7% or 14% depending on the scenario (Table 110). For Reach 6, the decline is 16% or 17%. For the future scenarios, for Reach 5, the discharge associated with a probability of exceedance of 0.45 declines by 10% for all scenarios (Table 110). For Reach 6, the decline is 8%.

Figure 94: Partial flood series' based on mean daily discharge, at the upper (Lingjiang) and lower (Jiaojiang) ends of the Lingjiang-Jiaojiang estuary. IQQM modelled current scenario and 5 future scenarios (see text for explanation).

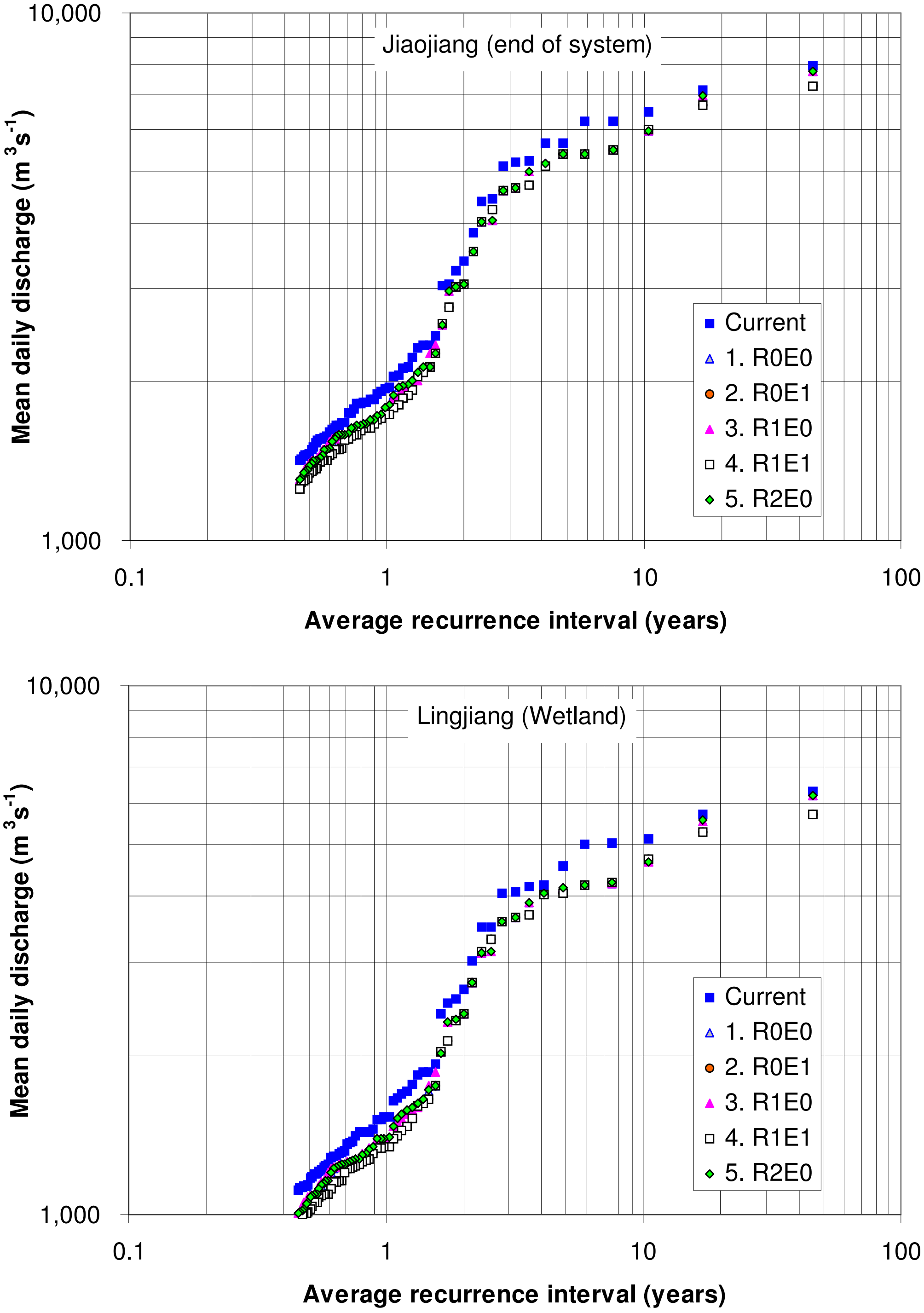


Table 110: Changes in frequency and magnitude of bankfull flows (P = 0.45, or 1 in 2.2 years ARI) for estuarine Reach 5 (Lingjiang) and Reach 6 (Jiaojiang) associated with alternate future scenarios of reservoir construction and operation. P = Probability of exceedance (events/year), Q_{DAILY} = Flood discharge peak (mean daily discharge in m^3s^{-1}). Future scenarios explained in text.

Reach	Index	Scenario					
		Current	1. R0E0	2. R0E1	3. R1E0	4. R1E1	5. R2E0
Lingjiang	P for Q_{DAILY} = 3,110 m^3s^{-1}	0.45	0.39	0.42	0.39	0.42	0.39
	Difference		-14%	-7%	-14%	-7%	-14%
	Q_{DAILY} for P = 0.45 events/yr	3,110	2,804	2,811	2,804	2,811	2,806
	Difference		-10%	-10%	-10%	-10%	-10%
Jiaojiang	P for Q_{DAILY} = 3,980 m^3s^{-1}	0.45	0.38	0.37	0.38	0.37	0.38
	Difference		-16%	-17%	-16%	-17%	-16%
	Q_{DAILY} for P = 0.45 events/yr	3,980	3,650	3,649	3,654	3,653	3,652
	Difference		-8%	-8%	-8%	-8%	-8%

Chapter 10: Comparison of Flow Recommendations with Tennant Method and IHA Indices

10.1 Tennant method

The only aspects of Tennant method recommendations (Table 88) that bore any resemblance to the recommendations made here were the basefow components (Low Flows and High Flows). For these, the Tennant management condition class that compared closest to the recommendations made here varied from “Poor” at Reach 1 downstream of Zhuxi Dam to “Excellent” at Reach 4 Yong’anxi upstream of Shifeng. Specific baseflow recommendations were not made for estuarine Reaches 5 and 6. It is interesting that the correspondence between the Tennant recommendations and the recommendations of this study changed in a systematic way in the downstream direction. This is because the Tennant method calculates values as a percentage of mean annual discharge, while for this study the baseflows were based on flow percentile, and the relationship between these two indices varies downstream, i.e. in the downstream direction, the flow exceeded 75% of the time increases as a percentage of the mean annual flow. This prevents consistent application of the Tennant method and is sufficient reason for not using it as a rapid method for estimating environmental flow needs.

10.2 IHA

The magnitudes, frequencies and durations of the recommended flow components were compared with the standard hydrological statistics calculated by the IHA (Table 89, Table 90, Table 91, Table 92, Table 93). To summarise, there was no set of IHA parameters that consistently predicted the recommended flow components. However, some statistics did give similar values in some cases, as described below.

The IHA 30-day minimum (IHA Parameter Group #2) closely predicted the Low Flows (Oct-Jan) components for Reaches 1, 2 and 3, and under predicted by 9% for Reach 4. The IHA 90-day minimum closely predicted the High Flows component for Reaches 1 and 2, and under predicted by 20% for Reaches 3 and 4. The EFC Low Flows over predicted the Low Flows (by a factor of around 2); the EFC Low Flows February value closely predicted the Low Flow Feb-Mar component; the EFC Low Flows (Apr-Sep) was a reasonable predictor of High Flows (Apr-Sep).

Table 111: Calculated discharges corresponding to the environmental flow – management condition classes defined by Tennant, compared with the baseflow recommendations made for this study. W = wet season (Oct-Mar), D = dry season (Apr-Sep). The Tennant values most closely corresponding to the recommendations of this study are shaded.

Tennant class and this study	Reach 1 Zhuxi DS Dam		Reach 2 Zhuxi End of Ck		Reach 3 Yong'anxi US Shifeng		Reach 4 Lingjiang (Wetland)	
	D	W	D	W	D	W	D	W
“Outstanding”	2.2	3.4	5.6	8.4	29	43	48	72
“Excellent”	1.7	2.8	4.2	7.0	22	36	36	60
“Good”	1.1	2.2	2.8	5.6	14	29	24	48
“Fair or degrading”	0.6	1.7	1.4	4.2	7.2	22	12	36
“Poor or minimum”	0.6	0.6	1.4	1.4	7.2	7.2	12	12
“Severe degradation”	0.0	0.6	0.0	1.4	0.0	7.2	0.0	12.0
This study	0.5	1.3	1.3 - 3.4	4.0	6.8 - 17.3	22	16 - 32	46

The IHA 30-day maximum closely predicted the Low Flow Pulse magnitude for Reaches 1 and 2, but for Reach 3 no statistic predicted the Low flow Pulse, and the IHA 90-day maximum was close to the High Flow Pulse (no pulses were recommended for Reach 4). For Reach 1, the EFC Small Flood over predicted the Bankfull magnitude by 25%, for Reach 2 it predicted Bankfull; for Reach 3 the EFC Small Flood over predicted the Bankfull magnitude by 88% and for Reach 4 it under predicted by 6%.

The lack of a consistent comparison between any of the IHA statistics and the recommended flow components was not unexpected. Firstly, this study used carefully selected seasons to match the local hydrological and ecological situation. Secondly, this study selected event magnitudes on the basis of hydraulic thresholds, and because the river’s geomorphologic characteristics naturally vary downstream, a consistent relationship between hydrological indices and relative water levels should not be expected. The IHA statistics could have been forced to predict our recommended flow magnitudes by adjusting the flow thresholds in the program, but the relevant point is that the information necessary to do this only becomes available *after* the hydraulic analysis has been undertaken.

The failure of hydrology-only methodologies to take into account the downstream change in the relationship between a river’s geomorphic and hydrologic characteristics (i.e. expressed as hydraulics) is a major weakness that cannot be easily overcome. This problem does not bode well for attempts to regionalize environmental flow recommendations on the basis of hydrology (i.e. ELOHA). One possible way of addressing this problem would be for the initial river classification (currently based on hydrology only in ELOHA) to also take geomorphology into account.

Chapter 11: Alternative Environmental Flow Regime Options

11.1 Introduction

Inclusion of the environmental flow rules in an IQQM model allows for an investigation of the impacts of the environmental flow recommendations on water availability and security of supply. Environmental flows normally reduce security of supply, so it is often the case that managers seek a recommendation from scientists on alternative (sub-optimal) environmental flow regime options that will achieve higher security of supply. Having environmental flow options available allows environmental outcomes to be traded off against security of supply. Reducing the environmental allocation requires prioritization of the identified assets and objectives to determine where reductions in the environmental allocation are best made. This process was undertaken here mainly as an example of how this might be done - it was not undertaken with a high degree of rigour. It must be clearly recognised that the sub-optimal environmental flow options represent a departure from the recommended flow regime, so they carry a higher risk that the identified assets will not be protected. Accepting a higher risk is a management decision, not a scientific one.

11.2 Methodology

In providing an alternative set of environmental flow recommendations, there are a number of options to consider. The relative potential to modify (i.e. reduce) a flow component depends on two things: the relative potential to improve security of supply, and the relative risk to the environment, of undertaking that reduction. If reducing a flow component has negligible impact on security of supply then there is little point in taking the environmental risk associated with the reduction. However, if reducing a flow component carries a high risk to the environment, then the reduction should not be considered.

The relative potential to improve security of supply (Table 112) was determined by roughly calculating the volumes of water required to supply the various flow components, and then determining the relative impact on total system savings by halving the flow component volume. The relative impact depends on the magnitude/frequency/duration characteristics of the component. For example, High Flows are of a relatively low magnitude, but long duration, so they account for a large percentage of the total flows, while Overbank flows are infrequent but of high magnitude so they also account for a high percentage of the total flows. This is a relatively coarse procedure (running the IQQM model for a range of scenarios would be a technically superior method, but it was considered impractical for this exercise).

The relative environmental impact of reducing the facets of a flow component (Table 112) was based on the principle that reducing a component's magnitude carried the greatest risk (as the necessary hydraulic threshold might not be achieved); Low Flows and High Flows magnitudes are low in the channel, and a 50% reduction is likely to create a severe reduction in available habitat, however the high flow season was considered less important than the low flow season in this respect; Bankfull and Overbank are less frequent than Pulses, so reducing their frequency was considered more detrimental than reducing frequency of Pulses (which would still occur at least once per year); we regarded Pulse duration as being possibly more important than frequency, as a certain duration is needed in order to allow the ecological process to be completed (i.e. water could be wasted if an inadequately short event was released, so it would be preferable to save the water for an effective event); Bankfull and Overbank components were specified with a peak duration of only 1 day, so total event duration cannot be reduced without increasing the rate of rise and fall.

Table 112: Relative potential to modify flow components (assuming equal reduction in all components) from perspective of improving security of supply and risk to environment.

Flow components (and hydrological facets)	Relative security of supply improvement	Relative risk to environment	Relative potential to modify	Rank potential to modify
Low Flow magnitude	Moderate	High	Nil	-
High Flow magnitude	Mod.-High	Moderate	Moderate	4
Low Flow Pulse magnitude	Low	High	Nil	-
Low Flow Pulse duration	Low	Moderate	Low	7
Low Flow Pulse frequency	Low	Low	Low	6
High Flow Pulse magnitude	Moderate	High	Nil	-
High Flow Pulse duration	Moderate	Moderate	Moderate	5
High Flow Pulse frequency	Moderate	Low	High	1
Bankfull magnitude	Mod.-High	High	Nil	-
Bankfull duration	Nil[†]	Moderate	Nil[†]	5[†]
Bankfull frequency	Mod.-High	Moderate	Mod.-High	2
Overbank magnitude	High	High	Nil	-
Overbank duration	Nil	Moderate	Nil	-
Overbank frequency	High	Moderate	Mod.-High	3

[†] Reach 3 an exception, with moderate potential to improve security of supply. Implement with High Flow Pulse duration reduction.

To achieve a ranking of potential to modify (reduce) the facets of the flow components, a simple risk assessment was undertaken based on the following rules:

i. Relative potential to modify was higher the lower was the risk to the environment and the higher was the potential for improving security of supply.
ii. Reduction in event magnitude resulted in High risk to the environment due the failure to achieve the threshold required to initiate the ecological/geomorphological process.
iii. A High risk to the environment resulted in no potential to modify the component.
iv. A Nil potential to improve security of supply resulted in no potential to modify the component.
v. Reduction in Pulse frequency was favoured over reduction in duration (as duration may be important to allow the ecological process to be completed).
vi. Pulse durations of 1 day cannot be reduced.
vii. Bankfull event duration can only be reduced for Reach 3, and Overbank duration cannot be reduced.
viii. The procedure for ranking options to modify the hydrological facet of flow components did not allow sequential ranking within a component, i.e. if reduction in frequency of a component ranked highly, the duration of that component could not be ranked immediately after it. The intention of this was to reduce the likelihood that the final alternative environmental flow regime would involve a reduction of both duration and frequency to any one component.

11.3 Alternative Options

The final rank of potential to modify (Table 112) enabled the generation of alternative environmental flow scenarios (Table 113, Table 114 and Table 115). As additional changes are progressively included (in the order indicated by the rank) the potential to achieve an improvement in security of supply increases but so too does risk to the environment. These potentials and risks are not numerically related. For this exercise we generated two alternative environmental flow options. The first (**Option 2: Sub-Optimal Environmental Flow Regime No. 1**) included the top 4 ranked changes, and the second (**Option 3: Sub-Optimal Environmental Flow Regime No. 2**) included the top 7 ranked changes. In each case, apart from a number of exceptions, the change was to halve the value of the hydrological facet of the flow component. The exceptions were:

- High Flow magnitude, which we felt carried excessive risk to the environment by halving, so we revised this to 25% reduction;
- The High Flow Pulse associated with spawning was regarded as high risk to the environment if reduced in any way, so it was not modified;
- The Overbank component is a special case. The way the environmental flows are specified, if Overbank is supplied, then Bankfull objectives are also considered to be achieved, so Bankfull does not have to be delivered. In this system Overbank would currently achieve little more than Bankfull, as most of the potential floodplain asset is protected by levees. Overbank is a realistic option only if some areas of floodplain are re-connected. Thus, the Overbank component was removed from consideration for the more severe alternative flow Option 3.

Chapter 12: Non-flow Related Issues

A number of non-flow related issues impact the Zhuxi-Jiaojiang system, and these represent threats to the success of any implemented environmental flow regime in achieving the objective of a healthy river. It is suggested that these issues be further investigated and appropriately managed.

12.1 Sand and gravel extraction

Sand and gravel extraction is widespread in the river system. The process appears to be one of removing the desired sand and gravel-sized fractions and leaving the coarser cobbles behind. Apart from the disruption caused by the process of extraction, the practice can have longer-term repercussions. The types of changes that can occur are:

- Loss of bed volume
- Change in the particle size of the bed material
- Disruption of armoured surface layers
- Alteration of natural bedforms that may be important habitats in their own right, or they may be important because they generate desirable hydraulic habitats under certain flow conditions
- Potential for extraction exceeding the rate of supply, leading to downstream or upstream progression of bed incision. Incision can be followed by a phase of widening

Table 113: Summary of Option 1: Recommended Environmental Flow Regime. BF can be omitted if OB implemented (for reaches where OB specified).

Component	Timing	Magnitude (m^3s^{-1})	Frequency (per year)	Duration (days at peak)	Magnitude condition	Frequency condition	Rise/event/fall (day/day/day)
Reach 1							
LF	Oct-Mar	0.5	Continuous			Or natural	
HF	Apr-Sep	1.3	Continuous			Or natural	
LFP	Oct-Dec; Jan-Mar	20	1 each period	1 day / period		Each year	2/1/2
HFP	Apr	20	2	2		Each year	1/2/2
HFP	May-Sep	20	4	2		Each year	1/2/2
BF	Anytime	177	0.52	1	524 inst. peak to be achieved	Long-term average	1/1/1
OB	Anytime	191	0.52	1	571 inst. peak to be achieved	Long-term average	1/1/1
Reach 2							
LF	Oct-Jan	1.3	Continuous			Or natural	
LF	Feb-Mar	3.4	Continuous			Or natural	
HF	Apr-Sep	4.0	Continuous			Or natural	
LFP	Oct-Dec; Jan-Mar	53	1 each period	2 days / period		Each year	2/2/2
HFP	Apr	53	1	2		Each year	2/2/2
HFP	May-Sep	53	4	2		Each year	2/2/2
BF	Anytime	397	0.58	1	1,011 inst. peak to be achieved	Long-term average	1/1/1
OB	Apr-Sep	428	0.58	1	1,102 inst. peak to be achieved	Long-term average	1/1/1
Reach 3							
LF	Oct-Jan	6.8	Continuous			Or natural	
LF	Feb-Mar	17.3	Continuous			Or natural	
HF	Apr-Sep	22.2	Continuous			Or natural	
LFP	Oct-Mar	96	4	4		Each year	2/4/3
HFP	Apr-Sep	146	6	7		Each year	2/7/3
BF	Anytime	948	1.3	1	1,289 inst. peak to be achieved	Long-term average	2/1/2
Reach 4							
LF	Oct-Jan	16.0	Continuous			Or natural	
LF	Feb-Mar	31.8	Continuous			Or natural	
HF	Apr-Sep	46	Continuous			Or natural	
BF	Anytime	3,184	0.45	1	3,980 inst. peak to be achieved	Long-term average	1/1/1

Table 114: Summary of Option 2: Sub-Optimal Environmental Flow Regime No. 1. BF can be omitted if OB implemented (for reaches where OB specified).

Component	Timing	Magnitude (m^3s^{-1})	Frequency (per year)	Duration (days at peak)	Magnitude condition	Frequency condition	Rise/event/fall (day/day/day)
Reach 1							
LF	Oct-Mar	0.5	Continuous			Or natural	
HF	Apr-Sep	1.0	Continuous			Or natural	
LFP	Oct-Dec; Jan-Mar	20	1 each period	1 day / period		Each year	2/1/2
HFP	Apr	20	2	2		Each year	1/2/2
HFP	May-Sep	20	2	2		Each year	1/2/2
BF	Anytime	177	0.26	1	524 inst. peak to be achieved	Long-term average	1/1/1
OB	Anytime	191	0.26	1	571 inst. peak to be achieved	Long-term average	1/1/1
Reach 2							
LF	Oct-Jan	1.3	Continuous			Or natural	
LF	Feb-Mar	3.4	Continuous			Or natural	
HF	Apr-Sep	3.0	Continuous			Or natural	
LFP	Oct-Dec; Jan-Mar	53	1 each period	2 days / period		Each year	2/2/2
HFP	Apr	53	1	2		Each year	2/2/2
HFP	May-Sep	53	2	2		Each year	2/2/2
BF	Anytime	397	0.29	1	1,011 inst. peak to be achieved	Long-term average	1/1/1
OB	Apr-Sep	428	0.29	1	1,102 inst. peak to be achieved	Long-term average	1/1/1
Reach 3							
LF	Oct-Jan	6.8	Continuous			Or natural	
LF	Feb-Mar	17.3	Continuous			Or natural	
HF	Apr-Sep	16.7	Continuous			Or natural	
LFP	Oct-Mar	96	4	4		Each year	2/4/3
HFP	Apr-Sep	146	3	7		Each year	2/7/3
BF	Anytime	948	0.7	1	1,289 inst. peak to be achieved	Long-term average	2/1/2
Reach 4							
LF	Oct-Jan	16.0	Continuous			Or natural	
LF	Feb-Mar	31.8	Continuous			Or natural	
HF	Apr-Sep	34.5	Continuous			Or natural	
BF	Anytime	3,184	0.23	1	3,980 inst. peak to be achieved	Long-term average	1/1/1

Table 115: Summary of Option 3: Sub-Optimal Environmental Flow Regime No. 2.

Component	Timing	Magnitude (m^3s^{-1})	Frequency (per year)	Duration (days at peak)	Magnitude condition	Frequency condition	Rise/event/fall (day/day/day)
Reach 1							
LF	Oct-Mar	0.5	Continuous			Or natural	
HF	Apr-Sep	1.0	Continuous			Or natural	
LFP	Oct-Dec; Jan-Mar	20	1 each period	1 day / period		Each year	1/1/1
HFP	Apr	20	2	2		Each year	1/2/2
HFP	May-Sep	20	2	1		Each year	1/1/1
BF	Anytime	177	0.26	1	524 inst. peak to be achieved	Long-term average	1/1/1
Reach 2							
LF	Oct-Jan	1.3	Continuous			Or natural	
LF	Feb-Mar	3.4	Continuous			Or natural	
HF	Apr-Sep	3.0	Continuous			Or natural	
LFP	Oct-Dec; Jan-Mar	53	1 each period	1 day / period		Each year	1/1/1
HFP	Apr	53	1	2		Each year	2/2/2
HFP	May-Sep	53	2	1		Each year	1/1/1
BF	Anytime	397	0.29	1	1,011 inst. peak to be achieved	Long-term average	1/1/1
Reach 3							
LF	Oct-Jan	6.8	Continuous			Or natural	
LF	Feb-Mar	17.3	Continuous			Or natural	
HF	Apr-Sep	16.7	Continuous			Or natural	
LFP	Oct-Mar	96	2	2		Each year	1/2/2
HFP	Apr-Sep	146	3	4		Each year	1/4/2
BF	Anytime	948	0.7	1	1,289 inst. peak to be achieved	Long-term average	1/1/1
Reach 4							
LF	Oct-Jan	16.0	Continuous			Or natural	
LF	Feb-Mar	31.8	Continuous			Or natural	
HF	Apr-Sep	34.5	Continuous			Or natural	
BF	Anytime	3,184	0.23	1	3,980 inst. peak to be achieved	Long-term average	1/1/1

12.2 Estuary channel dredging

The estuary requires constant dredging in order to overcome the naturally high rate of sediment deposition (with the vast majority of the sediment being sourced from the sea, not the Jiaojiang itself). However, dredging at a rate exceeding the deposition rate will deepen the estuary and this could have the effect of increasing the tidal range. The impacts of this have not been considered in any detail, but it will almost certainly have some impact.

12.3 Pollution

There are numerous point and non-point sources of pollution in the catchment (agricultural, urban and industrial). If pollution exceeds the limits of the biota, then the environmental flows will be obsolete.

Cold-water pollution is caused by cold water being released below reservoirs that have deep releases. This generally causes severe ecological disruption for a distance downstream, but it can be easily overcome by designing the reservoir with a multi-level offtake.

12.4 Over-fishing

According to the "Background report on Ecological Assets in the Jiaojiang Basin" prepared as part of the WET project, both freshwater and marine fisheries yields have stabilized over the last 10 years (1997-2006) at around 1,000,000 tons per annum. At the same time there has been a marked rise in aquaculture production. It is beyond the scope of this report to comment in detail on the sustainability of fishing practices in the Zhuxi and Jiaojiang system, although it is clear that ongoing monitoring of fisheries is warranted. Fisheries sustainability is exceptionally difficult to measure, but should take into account both yields, efforts, and the species that make up the catch. Declines in resource availability are often masked by increased catch effort or a shift toward more abundant species.

Aquaculture also warrants some mention. Major aquaculture species in the Taizhou region include several native species such as (*Ctenopharyngodon idellus*, *Aristichthys nobilis*, *Hypophalmicthys molitrix*). Given the ease with which these species can be spawned and reared in captivity, it is tempting to place a reduced importance on natural recruitment of wild populations, and the environmental conditions that maintain these populations. We would advise caution in this regard and point to the vast literature on the joint sustainable management of aquaculture and wild-fish stocks.

12.5 Catchment planning

This report has focused primarily on the flow related impacts associated with the construction of a dam on Zhuxi. It is possible to both recommend and implement an environmental flow regime to protect the assets of this system, but as development expands across the basin, maintaining ecological assets, particularly in the lower reaches will become a much greater challenge, both in terms of water availability, and in ensuring that diversions and releases are managed in a coordinated fashion. At the simplest level, the setting of a cap (stated in water volume) on basin-wide water use will provide the appropriate starting point from which to ensure water can be managed in a sustainable fashion. Without this initial constraint to ensure some water is available to protect environment assets, the development of environmental flow regimes simply will not be possible. These issues are discussed more broadly in WET Project (2007).

Chapter 13: Conclusion

The recommendations presented in this report identified the flow regime required to sustain, with relatively low risk, the ecological and geomorphic assets and processes in the Zhuxi-Jiaojiang system. The recommendations have been based around a number of existing methodologies outlined in the literature, which broadly combine information on ecological and other assets associated with the river system (in this case fish, vegetation, water quality and geomorphology) together with information that links these assets to aspects of the flow regime via hydraulic relationships. Using a combination of hydraulic and hydrological modeling, a specific set of flow rules were defined for input into an IQQM catchment-scale hydrological model. As well as providing environmental flow recommendations for this particular river system, this report is intended as a guide to assist practitioners with the methodological aspects of future environmental flow assessments undertaken in China.

The flow recommendations were compared against recommendations made by the Tennant method and against a raft of hydrological statistics calculated by the IHA software. There were no consistent relationships between the numbers produced by these hydrological methods and the environmental flow recommendations made in this study. This is largely because hydrology-only methods cannot account for the reality of the downstream change in the relationship between a river's geomorphic and hydrologic characteristics.

Inclusion of the environmental flow rules in an IQQM model allows for an investigation of the impacts of the environmental flow recommendations on water availability and security of supply. Environmental flows normally reduce security of supply, so it is often the case that managers seek a recommendation from scientists on alternative (sub-optimal) environmental flow regime options that will achieve higher security of supply. Having environmental flow options available allows environmental outcomes to be traded off against security of supply. Reducing the environmental allocation requires prioritization of the identified assets and objectives to determine where reductions in the environmental allocation are best made. This process was undertaken here mainly as an example of how this might be done - it was not undertaken with a high degree of rigour. It is stressed that this step was secondary to the main task undertaken in this report, which was to document a process for assessing the environmental flow requirements that would have a high probability of achieving the environmental objectives (i.e. protection of the identified environmental assets). It must be clearly recognised that the sub-optimal environmental flow options represent a departure from the *recommended* flow regime, so they carry a higher risk that the identified assets will not be protected. Accepting a higher risk is a management decision, not a scientific one.

This report provides a brief discussion of non-flow related issues pertaining to river health in the Zhuxi-Jiaojiang catchments. While these were not discussed in depth, it must be recognized that they will need to be addressed alongside the implementation of environmental flows if the desired flow-related objectives are to be achieved with a high degree of certainty.

Chapter 14: References

Apse, C., Arthington, A.H., Bledsoe, B.P., Bunn, S.E., Merritt, D., Naiman, R.J., Poff, N.L., Richter, B., Rogers, K.H., Tharme, R. and Warner, A.T. (2007) Ecological Limits of Hydrologic Alteration: An Approach for Setting Regional Environmental Flow Standards. Presented at North American Benthological Society 55th Annual Meeting. June 3-8, 2007, Columbia, South Carolina. URL: http://www.benthos.org/database/allnabstracts.cfm/db/Columbia2007abstracts/id/69 (accessed 1st December 2007).

Arthington, A.H. (1998) Comparative evaluation of environmental flow assessment techniques: review of holistic methodologies. LWRRDC Occasional Paper No. 26/98. Land and Water Resources Research & Development Corporation, Canberra, Australian Capital Territory.

Bi, A.H. and Sun, Z.L. (1984) A preliminary study on the estuarine processes in the Jiaojiang River, China. Journal of Sediment Research, 3, 12-26 (in Chinese).

Bovee K.D. (1982) A guide to stream habitat assessment using the Instream Flow Incremental Methodology. Instream Flow Information Paper 12, FWS/OBS-82/26. Cooperative Instream Flow Services Group, U.S. Fish and Wildlife Service, Fort Collins, CO.

Brown, C.A. and King, J.M. (2003) Environmental Flows: Concepts and Methods. Water Resources and Environment Technical Note C1, Davis, R. and Hirji, R. (eds), The World Bank, Washington, DC.

Bunn, S.E. and Arthington, A.H. (2002) Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management, 30, 492–507.

Bunte, K. (2004) State of the Science Review. Gravel Mitigation and Augmentation Below Hydroelectric Dams: A Geomorphological Perspective. Engineering Research Center Colorado State University, Fort Collin. Stream Systems Technology Center USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO.

Bureau of Reclamation (1999) Red River Valley Municipal, Rural, and Industrial Water Needs Assessment Phase I, Part B, Instream Flow Needs Assessment. Sheyenne River and Red River of the North, North Dakota and Minnesota, Final Appraisal Report. United States Department of the Interior, Bureau of Reclamation, Dakotas Area Office, Bismarck, ND, August.

Caissie, D., El-Jabi, N. and Bourgeois, G. (1998) Évaluation du débit réservé par méthodes hydrologiques et hydrobiologiques. Rev. Sci. Eau, 11(3), 347-364.

Chen, X. (2005) Statistical and geostatistical features of streambed hydraulic conductivities in the Platte River, Nebraska. Environmental Geology, 48: 693–701.

Department of Ecology (2003) Instream flow study methods used in Washington State. The Science Behind Instream Flows, Ecology, Washington State, Olympia, WA. URL: http://www.ecy.wa.gov/programs/wr/instream-flows/Images/pdfs/if-msum.pdf (accessed 1st December 2007).

Dudgeon, D. (1999) Tropical Asian Streams: Zoobenthos, Ecology and Conservation. Hong Kong University Press, Hong Kong.

Dunbar, M.J., Gustard, A., Acreman, M.C. and Elliott, C.R.N. (1998) Review of Overseas Approaches to Setting River Flow Objectives. Environment Agency R&D Technical Report W6B(96)4. Institute of Hydrology: Wallingford, UK.

Fernald, A.G., Landers, D.H. and Wiginigton Jr, P.J. (2006) Water quality changes in hyporheic flow paths between a large gravel bed river and off-channel alcoves in Oregon, USA. River Res. Applic., 22, 1111–1124.

Fu, N.P. and Bi, A.H. (1989) Discussion on the problems in the sediment transport of the Jiaojiang River. Journal of Sediment Research, 8, 51-57 (in Chinese).

Geist, D.R. (2000) Hyporheic discharge of river water into fall chinook salmon (Oncorhynchus tshawytscha) spawning areas in the Hanford Reach, Columbia River. Can. J. Fish. Aquat. Sci., 57, 1647–1656.

Gippel, C.J. (2001) Hydrological analyses for environmental flow assessment. In Ghassemi, F. and Whetton, P. (eds) Proceedings MODSIM 2001, International Congress on Modelling and Simulation, Modelling & Simulation Society of Australia & New Zealand, The Australian National University, Canberra, pp. 873-880.

Gippel, C.J. (2002) Geomorphic issues associated with environmental flow assessment in alluvial non-tidal rivers. Australian Journal of Water Resources, 5(1), 3-19.

Gippel, C.J. (2005) Environmental Flows: Managing Hydrological Environments. Chapter 191 in Encyclopaedia of Hydrological Sciences. Edited by M. Anderson, John Wiley & Sons, Ltd., Chichester, pp. 2953 – 2972.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., Gippel, C.J. and Nathan, R.J. (2004) Stream Hydrology: An Introduction for Ecologists. Second Edition, John Wiley & Sons, Chichester.

Groeneveld, D.P. and French, R.H. (1995) Hydrodynamic control of an emergent aquatic plant (Scirpus acutus) in open channels. Water Resources Bulletin, 31, 505-514.

Guan, W.B., Kot, S.C. and Wolanski, E. (2005) 3-D fluid-mud dynamics in the Jiaojiang Estuary, China. Estuarine. Coastal and Shelf Science, 65, 747-762.

Guan, W.B., Wolanski, E. and Dong, L. X. (1998) Cohesive Sediment Transport in the Jiaojiang River Estuary, China. Estuarine, Coastal and Shelf Science, 46, 861–871.

Herricks. E.E. and Suen, J.P. (2003) Ecological Design in Taiwan's Rivers: Performance Expectations Considering Hydrologic Variability. International Workshop on Ecohydraulics and Eco-rivers Engineering, Taipei, Taiwan, 2-3 October 2003, pp. 25-40. URL: http://www.wra.gov.tw/public/Attachment/41110465971.pdf (accessed 1st December 2007).

Hou, R., Beeton, R.J.S., Carter, R.W., Dong, X.G. and Li, X. (2007a) Response to environmental flows in the lower Tarim River, Xinjiang, China: Ground water. Journal of Environmental Management, 83, 371–382.

Hou, R., Beeton, R.J.S., Carter, R.W., Dong, X.G. and Li, X. (2007b) Response to environmental flows in the lower Tarim River, Xinjiang, China: An ecological interpretation of water-table dynamics. Journal of Environmental Management, 83, 383-391.

Hudson, N. (1971) Soil Conservation, Cornell University Press, Ithaca.

Hung, J.J., Chan, C.L. and Gong, G.C. (2007) Summer Distribution and Geochemical Composition of Suspended-Particulate Matter in the East China Sea. Journal of Oceanography, 63, 189-202.

Jiang, D. (2007) Progress in Environmental Flows Research Progress in Environmental Flows Research and Applications in China and Applications in China. Presented at the 10th International RiverSymposium and Environmental Flows CoOnference, Brisbane, September. URL: http://www.riversymposium.com/index.php?page=papers (accessed 1st December 2007).

Jiang, D., Wang, Wang, H. and Li, L. (2006) Progress in ecological and environmental water requirements research and applications in China. Water International 31(2), 145-156.

King County (2000) Hydrological change in the Green River near Palmer. WRIA 9 Steering Committee Draft. Steering Committee for Salmon Habitat Planning Green/Duwamish and Central Puget Sound Watershed. King County Department of Natural Resources and Parks - Water and Land Resources Division. URL: http://dnr.metrokc.gov/wrias/9/archive/0003/SteerCom/HydroAddendumRev.doc (accessed 1st December 2007).

King, J. Brown, C. and Sabet, H. (2003) A scenario-based holistic approach to environmental flow assessments for rivers. River Research and Applications, 19(5-6), 619-639.

Liu, J.P., X, K.H., Li, A.C., Milliman, J.D., Velozzi, D.M., Xiao, S.B. and Yang, Z.S. (2007) Flux and fate of Yangtze River sediment delivered to the East China Sea. Geomorphology, 85, 208–224.

McCarthy, J.H. (2003) Wetted perimeter assessment Shoal Harbour River, Shoal Harbour, Clarenville, Newfoundland. Report by AMEC Earth & Environmental Limited, St. John's, to SGE-Acres, Clarenville, NL, January. URL: http://www.env.gov.nl.ca/env/Env/EA%202001/pdf%20files/1059%20-%20WettedPerimeterAssessment.pdf (accessed 1st December 2008).

Merz, J.E. and Ochikubo L.K. (2005) Effects of gravel augmentation on macroinvertebrate assemblages in a regulated Californian river. River Research and Applications, 21, 61-74.

Naiman, R. J. and H. Decamps (1997) The ecology of interfaces: Riparian Zones. Annual Review of Ecology and Systematics, 28, 621-658.

Nelson, F.A. (1980) Evaluation of selected instream flow methods in Montana. Proceedings of the Annual Conference of the Western Association of Fish and Wildlife Agencies, pp. 412-432.

Nilsson , C. and Svedmark, M. (2002) Basic principals and ecological consequences of changing water regimes: riparian plant communities. Environmental Management, 30, 468-480.

Norriss, J.V., Tregonning, J.E., Lenanton, R.C.J. and Sarre, G.A. (2002) Biological synopsis of the black bream, Acanthopagrus butcheri (Munro) (Teleostei: Sparidae) in Western Australia with reference to information from other southern states, Fisheries Research Report No. 93. Department of Fisheries. Perth, WA.

Orth D.J. and Maughan O.E. (1981) Evaluation of the “Montana Method” for recommending instream flows in Oklahoma streams. Proc. Okla. Acad. Sci., 61, 62-66.

Orth, D.J. and Leonard, P.M. (1990) Comparison of discharge methods and habitat optimization for recommending instream flows to protect fish habitat. Regulated Rivers, 5, 129-38.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. and Stromberg, J.C. (1997) The natural flow regime, a paradigm for river conservation and restoration. BioScience, 47, 769-784.

Poff, N.L., Olden, J.D., Pepin, D.M. and Bledsoe, B.P. (2006) Placing global stream flow variability in geographic and geomorphic contexts. River Research and Applications, 22, 149-166.

Poole, G.C., Stanford, J.A., Running, S.W. and Frissell, J.A. (2006) Multiscale geomorphic drivers of groundwater flow paths: subsurface hydrologic dynamics and hyporheic habitat diversity. J. N. Am. Benthol. Soc., 25(2), 288–303.

Pyrce, R. (2001) Hydrological Low Flow Indices and their Uses. WSC Report No. 04-(2004) Watershed Science Center, Trent University. Symons Campus, Peterborough, Ontario, August. 33 p. URL: http://www.trentu.ca/iws/documents/LowFlowOntRpt2004.pdf (accessed 1st December 2007).

Reid, L.M. (1989) Erosion of Grassed Hillslopes, University of Washington, Washington.

Richter, B.D. and Thomas, G.A. (2007) Restoring environmental flows by modifying dam operations. Ecology and Society, 12(1): 12. URL: http://www.ecologyandsociety.org/vol12/iss1/art12/ (accessed 1st December 2007).

Richter, B.D., Baumgartner, J.V., Powell, J. and Braun, D.P. (1996) A Method for Assessing Hydrologic Alteration Within Ecosystems. Conservation Biology, 10, 1163-1174.

Richter, B.D., Baumgartner, J.V., Wigington, R. and Braun, D.P. (1997) How much water does a river need? Freshwater Biology, 37, 231-249.

Richter, B.D., Warner, A.T., Meyer, J.L. and Lutz, K. (2006) A collaborative and adaptive process for developing environmental flow recommendations. River Research and Applications, 22, 297-318.

SKM, CRC for Freshwater Ecology, Freshwater Ecology and Lloyd Environmental Consultants (2002) The FLOWS Method – a method for determining environmental water requirements in Victoria. Report prepared by Sinclair Knight Merz, the Cooperative Research Centre for Freshwater Ecology, Freshwater Ecology (NRE) and Lloyd Environmental Consultants. Department of Natural Resources and Environment, Melbourne.

Smakhitin, V.U. (2001). Low flow hydrology: a review. Journal of Hydrology, 240, 147–186.

Stewardson, M.J. and Gippel, C.J. (1997) In-stream Environmental Flow Design: A Review. Report to the Hydro-Electric Corporation, Tasmania. Department of Civil and Environmental Engineering, The University of Melbourne, 99 pp.

Surian, N. and Cisotto, A. (2007) Channel adjustments, bedload transport and sediment sources in a gravel-bed river, Brenta River, Italy. Earth Surf. Process. Landforms, 32, 1641–1656.

Tang, M., Huang, D., Huang, L., Xiang, F. and Yin, W. (1989) An evaluation of the hydraulic characteristics of the eggs of grass carp, black carp, silver carp and bighead carp and a preliminary prediction of the incubation conditions for them in hte proposed Three Gorges reservoir. Reservoir Fisheries, 4, 26-30.

Tennant, D.L. (1976) Instream flow regimens for fish, wildlife, recreation and related environmental resources. Fisheries, 1(4), 6-10.

Tharme, R.E. (2003) A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Research and Applications, 19(5-6), 397-441.

The Nature Conservancy (2007a) Indicators of Hydrologic Alteration Version 7 User's Manual. The Nature Conservancy, Arlington, VA. URL: http://www.nature.org/initiatives/freshwater/conservationtools/art17004.html (accessed 1st December 2007).

The Nature Conservancy (2007b) Ecological Limits of Hydrologic Alteration Integrating Environmental Flows with Regional Water Management. The Nature Conservancy, Arlington, VA. URL:

Wang, X, Zhang, Y. and Liu, C. (2007) Water quantity-quality combined evaluation method for rivers' water requirements of the instream environment in dualistic water cycle. A case study of Liaohe River Basin. Journal of Geographical Sciences, 17(3).

Wang, X. (2006) Research on Ecological Water Requirements of China's River Courses. Australia-China Environment Development Program. Water Entitlements and Trading Project, September.

Wei, Q., Ke, F., Zhang, J., Zhuang, P., Luo, J., Zhou, R. and Yang, W. (1997) Biology, fisheries, and conservation of sturgeons and paddlefish in China. Environmental Biology of Fishes, 48, 241-255.

Welcomme, R.L., Winemiller, K.O. and Cowx, I.G. (2006) Fish environmental guilds as a tool for assessment of ecological condition of rivers. River Research and Applications, 22, 377-396.

Wellcome, R.L. (1985) River Fisheries. FAO Technical Bulletin 262, FAO, Rome.

WET Project (2007) Water Entitlements and Trading Project, Phase 2. Mid-Project Report, China, August.

Wu, F.C. and Chou, Y.J. (2004). Tradeoffs associated with sediment-maintenance flushing flows: a simulation approach to exploring non-inferior options. River Research and Applications, 20, 591 – 604.

Xie, Y., Li, Z. William, G. and Li, P. (2001) Invasive species in China – an overview. Biodiversity and Conservation, 10, 1317-1341.

Xue, Y.Q., Zhang, Y., Ye, S.J., Wu, J.C. and Li, Q.F. (2005) Land subsidence in China. Environmental Geology, 48, 713–720.

Zhang, J. and Liu, C.L. (2002) Riverine Composition and Estuarine Geochemistry of Particulate Metals in China—Weathering Features, Anthropogenic Impact and Chemical Fluxes. Estuarine, Coastal and Shelf Science, 54, 1051–1070.

Zhang, X., Zhong, Y. and Chen, J. (2003) Fanwort in eastern China: An invasive aquatic plant and potential ecological consequences. Ambio, 32, 158-159.

Zhong, Y. and Power, G. (1996) Environmental impacts of hydroelectric projects on fish resources in China. Regulated Rivers: Research and Management, 12, 81-98.

Zhou, C., Liang, Z. and Huang, H. (1980) Ecological features of the spawning of certain fishes in the Hanjiang River after the construction of dams. Acta Hydrobiologia Sinica, 7, 175-188.

Appendix: Table of Fish Species Included in Detailed Review

Family	Scientific name	Common name	Adult habitat	Spawning habitat	Larval habitat	Feeding	Migratory pattern	Spawning period
Engraulidae	Coilia mystus	Osbeck's grenadier anchovy	coastal waters; easturies; mid river reaches				Amphidromous	May
Engraulidae	Coilia ectenes	Tapertail anchovy	coastal waters; easturies; mid river reaches	among reeds, mid river reaches	eggs drift to eastuary	omnivorous (planktivore)	anadromous	May-August; 3 times
Clupeidae	Macrura reevsii	Hilsa Herring	coastal waters; easturies	freshwater, among reeds	tide pools; estuaries	zooplankton	Anadromous	May-July
Plecoglossidae	Plecoglossus altivellis	Sweet fish, Ayu	coastal waters, estuaries	freshwater, lower reaches, silt free gravel beds	drift to sea	omnivorous (benthivore)	Anadromous	March (spring)
Sparidae	Acanthopagrus schlegelii	Black Porgy	coastal waters, estuaries	upper estuary, seagrass beds?	seagrass beds?	zooplankton, benthos	Anadromous	spring-summer
Bagridae	Anguilla japonica	Freshwater eel	deep pools in rivers	Ocean	ocean-estuary	fish & invertebrates	Catadromous	Autumn
Bagridae	Anguilla marmoratus	Giant mottled or marbled eel	deep pools in rivers	Ocean	ocean-estuary	fish & invertebrates	Catadromous	spring?
Serranidae	Lateolabrax japonicus	Japanese sea bass	inshore reefs	estuaries			Catadromous	
Mugilidae	Liza so-iuy	Far Eastern Mullet	lowland river	estuaries			Catadromous	
Periophthalmidae	Boleophthalmus pectinirostris	Blue spotted mud skipper	intertidal mudflats	mudflats	mudflats	omnivorous	Non-migratory	autumn?

Family	Scientific name	Common name	Adult habitat	Spawning habitat	Larval habitat	Feeding	Migratory pattern	Spawning period
Sciaenidae	Larimichthys croceus	Large yellow croaker	coastal waters, estuaries			fish, zooplankton	oceanodromous	October-January
Cyprinidae	Aristichthys nobilis	Bighead carp	riverine	flowing waters; upper reaches;	riverine	zooplankton; benthic and planktonic	Potamodromous	summer?
Cyprinidae	Ctenopharyngodon idellus	Grass carp	riverine	flowing waters; upper reaches;	lowland rivers	vascular plants; algae	Potamodromous	
Cyprinidae	Hypophalmichthys molitrix	Silver Carp	riverine	flowing waters; upper reaches;		phytoplankton ; detritus	Potamodromous	spring (April-May)
Cyprinidae	Mylopharyngodon piceus	Black carp	rivers; lakes; reservoirs	flowing waters; upper reaches;	lowland rivers	zooplankton; benthic and planktonic	Potamodromous	April-May