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Use of hydraulic rating to set environmental flows in the Zhangxi River, China

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Key words: environmental flow, water allocation, water supply, hydropower, environmental impact assessment

Abstract

Ningbo city, China, is a rapidly growing residential and industrial centre, with a current population of 4 million. Its development has required a major water supply expansion programme providing 400,000 m^3 of water per day from the upper reaches of the Zhangxi River by means of a cascade of reservoirs. Water resources management is achieved through operation of two major reservoirs, Jiaokou (75 million m^3) and Zhougongzhai (93 million m^3). Water is released from the reservoirs, via turbines (generating hydropower), for local industry, irrigated agriculture and public supply along the lower reaches of the River and to maintain the river ecosystem. Surveys of local residents along the Zhangxi River showed its important role in aspects of life, social activity, culture and leisure. Analysis of ecological monitoring data demonstrated the diverse nature of fish, plants and invertebrates within the river. Some elements of the ecosystem have a high local economic value to local people. This paper reports an assessment of the environmental flow needed to support key species in the river ecosystem. It employs hydraulic ratings to define sections of the river where flow velocity reaches 0.5 ms^{-1}, required to stimulate spawning of the moonlight fish, an economically important and indicator species in the river. In two out of 6 cross-sections studied, flow releases from the reservoirs meet the needs of fish. The reservoirs reduce flood flows, which may lead to a loss of deep pools that are essential for the fish to survive during winter months.

Introduction

Adequate water is essential for human existence, including our health, growing our food, supporting our industries and maintaining ecosystems that provide goods and services and much of our quality of life (Acreman, 2001). However, in most regions of the world, precipitation varies through the year and between years, thus storage of water is often required. Some regions have extensive aquifers that provide a constant water source, in other areas artificial water storage may be necessary, particularly as climatic variability is likely to increase in the future (IPCC, 2007). Some 45,000 large dams[1] have been built worldwide to provide public, agricultural and industrial water supply, to generate hydropower and control floods. However, dams have been controversial. The Millennium Ecosystem Assessment (2005) showed that many ecosystems were being degraded or lost, with aquatic systems suffering particularly from the withdrawal of water for direct human needs, with many impacts directly resulting from fragmentation by dams (Nilsson *et al*., 2005) For example, the Aswan dam in Egypt, whilst generating power and providing irrigation water, has led to the loss of fisheries, and caused coastal erosion and salt-water intrusion (Acreman, 1996). The report of the World Commission on Dams (2000) concluded that dams have made an important and significant contribution to human development, but the social and environmental costs have, in too many cases, been unacceptable and often unnecessary. The Commission's report also provides principles and guidelines for decision-making on water infrastructure, including the release of environmental flows; defined as the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits' (www.eflownet.org, Dyson *et al*., 2003). Hydro-ecological analysis has shown that all elements of the flow regime influence freshwater ecosystems, including floods, average and low flows (Junk *et al*. 1989; Richter *et al.,* 1997; Poff *et al*., 1997; Biggs *et al*., 2005; Arthington *et al*., 2006; Kennen *et al*., 2008). The World Bank as embraced the need for environmental flows as a part of its safeguards policy (Brown and King, 2003; Acreman, 2003). Environmental flows are also included within sustainability guidelines produced by the International Hydropower Association (2004) to promote greater consideration of environmental, social and economic aspects in the sustainability assessment of new hydro projects and the management and operation of existing hydro-power schemes.

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[1] Large dams (as defined by the International Commission on Large Dams, ICOLD) are those dams more than 15 m high or with a storage capacity of more than 3 million m^3.

Since major reforms in 1978, the economy of China has grown very rapidly at an average annual rate of 9 percent a year and peak rates of 13 percent, quadrupling per capita income in the last 15 years and bringing many millions of people out of poverty. This has been achieved by substantial investment in high-tech industries and associated infrastructure, including housing, roads and dams. One of the potential negative consequences of rapid industrial development is the degradation of the atmospheric, terrestrial and aquatic environments. In March 1998, the State Environmental Protection Administration (SEPA) was officially upgraded to a ministry-level agency, reflecting the growing importance the Chinese Government places on environmental protection. Beginning in 2006, the government greatly expanded resources allocated to environmental protection and a series of new laws has been passed and their enforcement expanded.

Many Chinese scientists are now working on environmental flows and public awareness has greatly increased over the last five years. For example, the concept of environmental flow was introduced by Tang (1989) in his research on water resources of Ta Li Mu basin. It also has been integrated with the "Keeping the health life of the Yellow River" campaign (Li, 2004) of Yellow River (Huang He) Conservancy Commission (*www.yellowriver.gov.cn*). There is no direct law addressing environmental flows in China, though two laws issued by the China State Council in 2006 have a direct effect of ensuring environmental flow (quantity issues).

1. The Regulation of Water Abstraction Permit Management and Water Resources Fee Collecting, which stipulated the principle of total water abstraction control of a river basin and an administrative district to prevent over abstraction of surface water and groundwater.
2. The Regulation of Yellow River Water Allocation and Regulating to prevent Yellow River from drying up and ensure environmental flow through collective measures.

Although the concept of 'keeping the river healthy' has been generally accepted in China, the exact definitions of 'healthy river' criteria are still under discussion; for example, each of the Yellow River Commission, the Yangtze River Commission, the Pearl River Commission has developed different healthy river indicator systems (Liu, 2006; Wu, 2007; Jin 2009). Although research activity on environmental flows is high in China, much work has been of a qualitative and descriptive nature, rather than quantitative and science-based and the temporal and spatial dimensions have not been clearly addressed. A particular area lacking research effort is the link between water quantity and water quality (Feng, 2002). There is also a paucity of academic coordination on environmental flows, which has meant poor consistency and conformity in research. The integration of environmental flows within water resources management has yet to be achieved; specifically, that flow releases from reservoirs for other purposes, such as abstraction downstream for irrigation, may maintain good ecosystems (Song, 2003).

The Ningbo project

The Ningbo Water and Environment Project (NWEP) was approved by the World Bank in 2005 as a requirement for local economic growth. The NWEP includes component for the Ningbo Water Supply Project, which consists of a 400,000 m^3d^{-1} water treatment plant and 84 km of transmission mains. The source of water for the treatment plant is Jiaokou reservoir, completed in 1980, which has an active storage capacity of 75 million m^3 and is fed by the Zhangxi River. To provide additional storage, the NWEP included construction of the Zhougongzhai Reservoir, completed in 2006, located approximately 15 km upstream of Jiaokou reservoir on the Zhangxi River, which has an active storage capacity of 93 million m^3 (World Bank, 2005) The two reservoirs are conjunctively operated to supply water to the Ningbo as well as meet local downstream water demands. The Zhangxi River joins the much larger Fenhua River approximately 16 km downstream from Jiaokou reservoir, defining a reach potentially impacted by changes in its flow regime.

The average annual inflow into Jiaokou reservoir is 284 million m^3 and the new water treatment plant can divert over half of this (180 million m^3) when in operation. The natural mean flow in Zhangxi River downstream of Jiaokou reservoir ranges from 4 m^3s^{-1} during the winter to 20 m^3s^{-1} in late summer. Current flows (after reservoir construction) range from 2-4 m^3s^{-1}, showing large reductions from the natural flow during the wet summer months. Ecological baseline monitoring indicated that although the Zhangxi River is not particularly ecologically rich and does not hold rare or endangered species, it does support a viable aquatic ecosystem, including fish, invertebrates and plants that are important to local people.

The NWEP Environmental Management Plan calls for more ecological monitoring along the Zhangzi River during implementation, including a reassessment of necessary environmental flows, and potentially recommendations for improving reservoir operations to maintain the river ecosystem while still meeting other needs including water diversions.

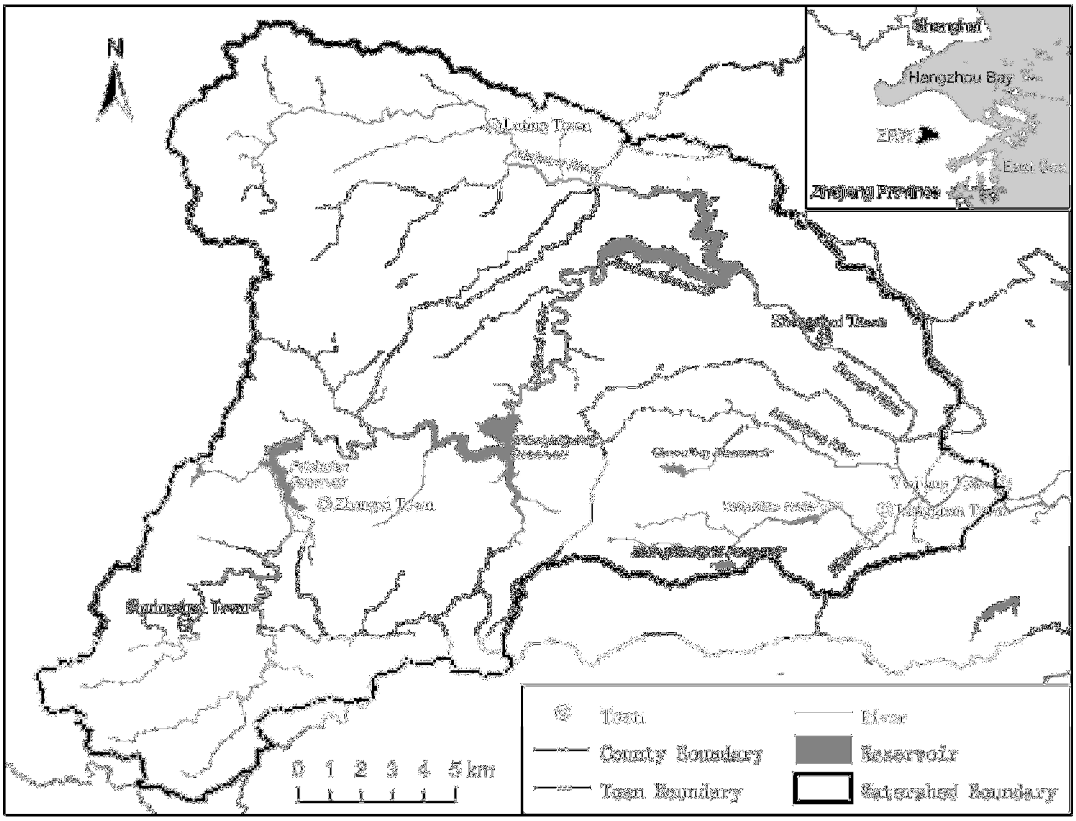

Figure 1 Zhangxi River catchment

The Zhangxi catchment

The Zhangxi River catchment lies in the upstream of the Yinjiang River basin, which is a tributary of the Fenghua River. It drains from the Siming mountains that rise to 700 m, to the coastal plain near to Ningbo city (Figure 1). The mountains are forested (containing the Siming Mountain National Forest Park) with an alpine climate.

The Zhangxi River has two main upstream braches; the Dajiao Brook, which is 44.9 km in length and drains an area of 168 km^2, and the Xiaojiao Brook, which is 24 km long and drains 91km^2. Dajiao Brook and Xiaojiao Brook converge at the Jiaokou reservoir. Only the reach between Jiaokou reservoir and its confluence with the Yinjiang River (marked by a 10th century weir called Tashan) is actually called the Zhangxi river; this defines the limits of this study (Figure 1). Lower tributaries include the Longwang and Huanxi Rivers. The Zhangxi River channel is not natural, but has been altered considerably over many centuries. Tashan weir is sited at the tidal limit of the Zhangxi River and prevents salt water intrusion to water supply intakes at Yinjiang. There are numerous other weirs along the River that elevate the river level to enable diversions to hydropower plants and irrigated land. These weirs have altered the hydraulic behaviour of the river channel. This has led to a change in the natural species of animal and plants that make-up the river ecosystem.

Water resources assessment approach

Figure 2 shows the framework for defining flow requirements for the Zhangxi River downstream of Jiaokou reservoir. There are two major components: direct water requirements and indirect water requirements. Direct water requirements are to support local irrigation, public supply and industry. Indirect water requirements consist of flows to maintain the river ecosystem and its social and cultural values, including water quality. All water released from the reservoir to the river goes through turbines and generates hydropower. The exception to this is during large floods when water may pass the dam spillway. A high proportion of the direct water use is not consumed, but returned to the river as domestic waste water, industrial effluent and irrigation drainage, thus the water consumed is considered as the actual overall requirement of direct use (assuming that the quality of the returned water is sufficiently good to meet other demands), although there are short reaches between off-takes and return points.

Water requirements for local people vary slightly between years and were determined from records of abstraction at water treatment plants; seasonal variations are considered insignificant. Water requirements for local irrigation exhibit a strong seasonal character, with major water use from May to September; only the water needs during this period were considered in the water allocation calculations. Water requirements for local industry also have certain seasonal characteristics, so their monthly distribution was considered.

Since direct water requirements can be readily calculated from available data without the need for new analysis, we focus in this paper on the estimation of water quantity requirements for the river ecosystem.

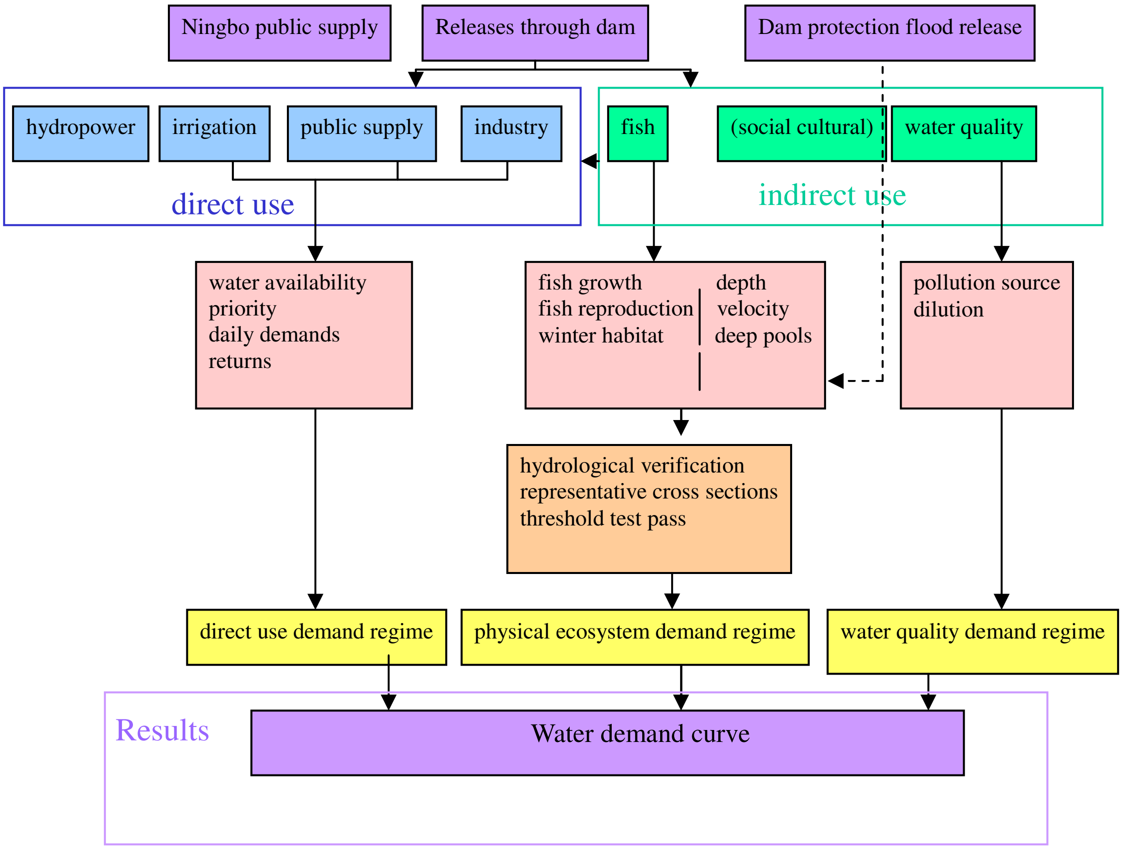

Figure 2. Schematic diagram of water demand assessment approach

Flow needs of the Zhangxi River ecosystem

Biological surveys of the Zhangxi River revealed a diverse range of species and high biomass. There are 10 fish species that exploit different habitat, mainly lotic fish and those preferring slow flow or still waters. Dominant species are *Distoechodon tumirostris* (a sub-tropical cyprinid fish), *Cyprinus carpio* (Common carp), *Anguilla spp*. (eel), *Eriocheir sinensis* (Chinese river crab) and *Pelodiscus sinensis* (soft-shelled turtle). Analysis was undertaken of the flow needs of various elements of the ecosystem, based on available scientific knowledge and biological surveys combined with the observations and experience of local people and fishermen concerning the flow conditions under which different species have been found. The moonlight fish (*Distoechodon tumirostris*) in particular needs high velocities during the spawning season (Guo, 2008). This fish was considered to be the most sensitive species to flow in the Zhangxi River; thus it was adopted as an indicator of ecosystem health, assuming that protection of habitat for this species would protect habitat for all river ecosystem components. During the reproduction period (April-May) females are stimulated to spawn by fast flowing (0.5-1.5 ms^{-1}) shallow water. Moonlight fish fry/juveniles have no minimum flow requirement, but have limited swimming ability and so prefer slow velocities; they can survive high flows if they can access slow flow refuge habitat. During the winter period (October-March) the fish primarily inhabit deeper sections of the river, particularly large pools, where velocities are low. Two types of pool habitat exist within the Zhangxi River; deep water upstream of weirs and pools created by bed sediment scour during floods. It is recognised that floods have a dominant role in the ecosystem by maintaining channel geometry, particularly the deep pools in the river channel. After completion of Jiaokou reservoir, the number and depth of deep natural pools were greatly reduced; there are around half of the deep pool left and their depth has reduced from 6 m to 3 m. Most fish can survive through the winter provided the water depth exceeds 2 m. Seasonal requirements of the moonlight fish are summarised in Table 1.

Table 1 Summary of habitat needs of the moonlight fish

Life stage	Season	Hydraulic needs	Notes
Spawning	April-May	High velocity 0.5-1.5 ms^{-1}	High velocity and turbulence across the fishes body stimulates it to spawn.
Growth of young	June-July	Low velocities	the young fish have limited swimming ability
Refuge habitat	August-September	Deep pools with low velocities	During typhoon-generated floods
Over-wintering	October-March	Deep pools	

The moonlight fish is potentially limited by physical habitat conditions that result from a combination of alterations to flow (due to dams) and channel geometry (due to weirs). To address this issue along the Zhangxi River, six cross-sections were chosen in straight channel reaches without back-water effects from man-made structures nearby and without vegetation along the river, to faciltiate flow gauging (Figure 3). At each cross-section, the vertical mean velocity (U) and water depth (D) were measured at several points across the river. The mean flow velocity was calculated by recording point velocities at 0.6D (where D<0.5 m) or 0.2D, 0.6D and 0.8D (where D>0.5 m) using an impeller current meter. Thus the vertical mean velocity (U) in that water column is either 0.6D or 0.25(0.2D+2×0.6D+0.8D). Table 2 summaries geometrical parameters and flow conditions during the measurement on 25 June 2009.

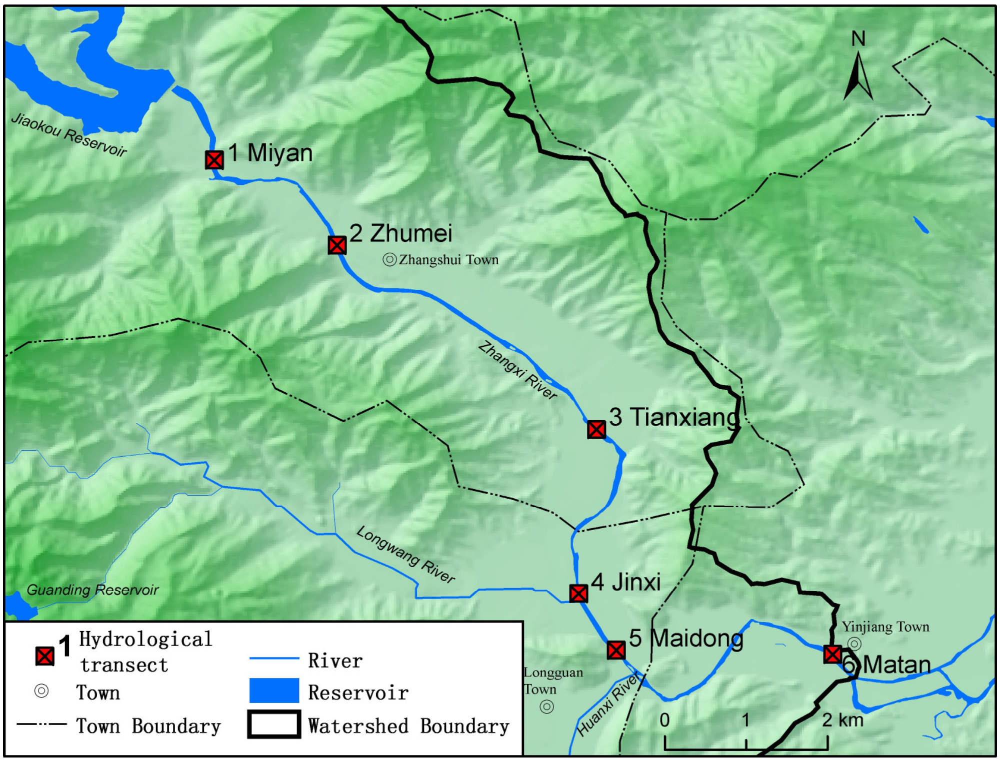

Figure 3 Location of cross-sections of Zhangxi River

Table 2 also shows that the discharge measured on that day decreases from 7.17 m^3s^{-1} to 2.34 m^3s^{-1} due to downstream water demand and flow control structures along the river except in Maidong cross-section where increase in discharge is due to inflow from the Longwang river upstream of that cross-section. The measured vertical mean velocity profiles across the five cross-sections are shown in Figure 4. It shows that the maximum vertical mean velocities for Miyan, Zhumei, Tianxiang and Jinxi cross-sections are less than minimum requirement of 0.5 ms^{-1} and for Maidong and Matan, they are slightly higher than 0.5 ms^{-1} in some parts of cross-section.

Table 2 Cross-sectional geometrical parameters and flow conditions

	Cross-section name	Water surface width (m)	Flow area (m^2)	Water depth at deepest point (m)	Discharge Q (m^3s^{-1})	Maximum vertical mean velocity (ms^{-1})
1	Miyan	70.40	44.73	1.10	7.17	0.33
2	Zhumei	39.20	22.28	1.14	4.57	0.28
3	Tianxiang	55.60	21.03	0.77	3.52	0.27
4	Jinxi	58.00	20.34	0.57	3.29	0.32
5	Maidong	51.03	11.33	0.86	4.46	0.66
6	Matan	46.80	13.81	0.86	2.34	0.73

To define the required discharge required to produce adequate velocities for moonlight fish spawning, hydraulic geometry analysis was undertaken. Stage-discharge and vertical mean velocity predictions were produced for each cross-section using a quasi 2D numerical model, calibrated using only the field data collected on 25 June 2009. The model numerically solves the depth-averaged Navier-Stokes equation for the downstream motion of flow (Rameshwaran and Shiono, 2004; 2007). To solve model equation, the average channel bed slope is calculated using the channel profile as 0.0017, the Eddy viscosity is modelled using the standard constant viscosity equation and the Darcy-Weisbach roughness values across the cross-section is calculated using measured data and assumed to be same for other flow depths. In straight, wide channels, with flows remaining within the banks, the secondary flow effects are negligible in the model. It also assumed that there is no backing-up of flow in these cross-sections due to flow control structures along the river.

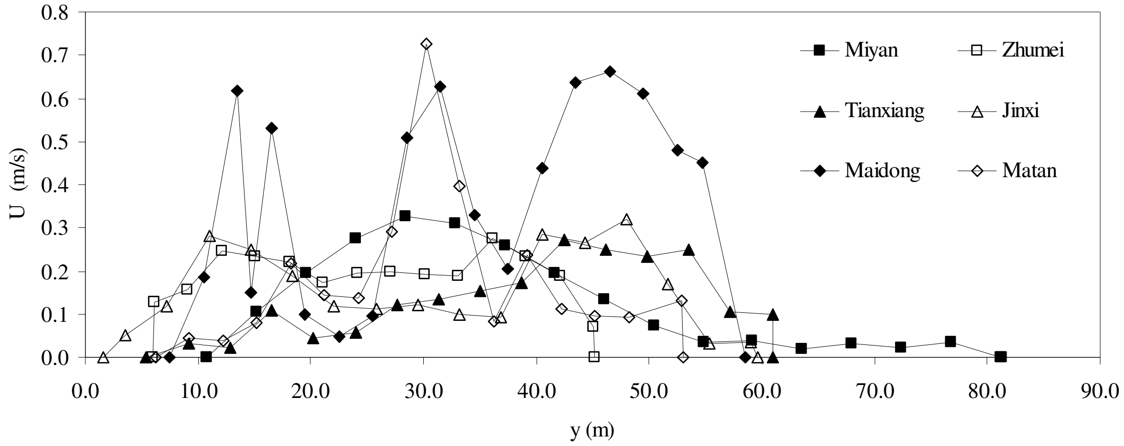

Figure 4 Measured vertical mean velocity (U) profiles across cross-sections

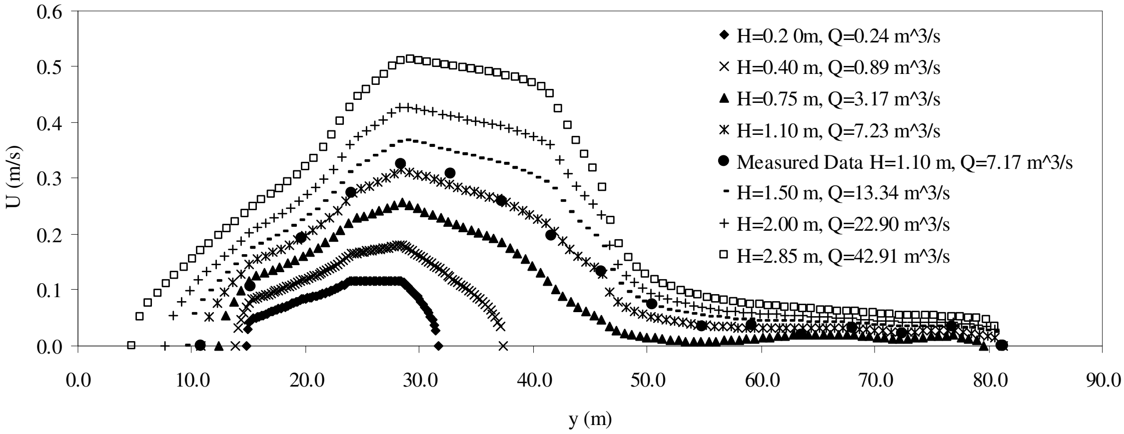

Figure 5 Predicted vertical mean velocity (U) profiles across Miyan cross-section

The model output for varies stages for the Miyan are shown in Figure 5 and Table 4 summaries the required stage-discharge to get 0.5 ms^{-1} vertical mean velocity at each cross-section which is mainly govern by cross-sectional geometrical and roughness parameters.

Table 3 Required stage-discharge to achieve 0.5 ms^{-1} velocity

	Cross-section name	Depth at deepest point (m)	Discharge Q (m^3/s)
1	Miyan	2.85	42.91
2	Zhumei	3.85	69.77
3	Tianxiang	2.77	43.67
4	Jinxi	1.17	14.90
5	Maidong	0.70	1.34
6	Matan	0.75	1.26

The hydraulic analysis also demonstrated that the depth of water upstream of the weirs varied little with flow, whereas depth downstream of weirs was sensitive to flow change with significant depth only occurring during floods. Slow velocity (<0.5 ms^{-1}) habitat for growth of young moonlight fish is abundant in the Zhanxi River, with a range of depths, shallow areas and deep areas with slow velocity to grow.

Hydrological analysis

Flow on the Zhangxi river are recorded at flow gauging station at the outflow of Jiaokou reservoir since completion of the dam in 1980. To complement these data, flows under natural conditions (without the dam in place) were simulated using the Xinan rainfall-river flow model and data from 7 rainfall stations. Examples of modelled natural flow data and observed data are shown in Figure 4 for 2003, which was a dry year. It can be seen that natural peak flows can reach 57 m^3s^{-1}, whereas actual flows rarely exceed 10 m^3s^{-1}. Figure 5 also shows that after construction of Jiaokou reservoir, the minimum flow of Zhangxi River often exceeds the natural flow. Small and medium sized floods are drastically reduced, which is likely to affect sediment transport. This is likely to be the cause of a loss of half the deep natural pools and a reduction in the depth of remaining pools. However, Zhougongzhai and Jiaokou reservoirs cannot attenuate major floods entirely, especially those resulting from high intensity storms during typhoons in August and September. During these events, bed scour is likely to continue. Suitable habitat for growth and over-wintering exists upstream of weirs and in surviving deep pools that are not dependent on critical levels of flow releases from the reservoir.

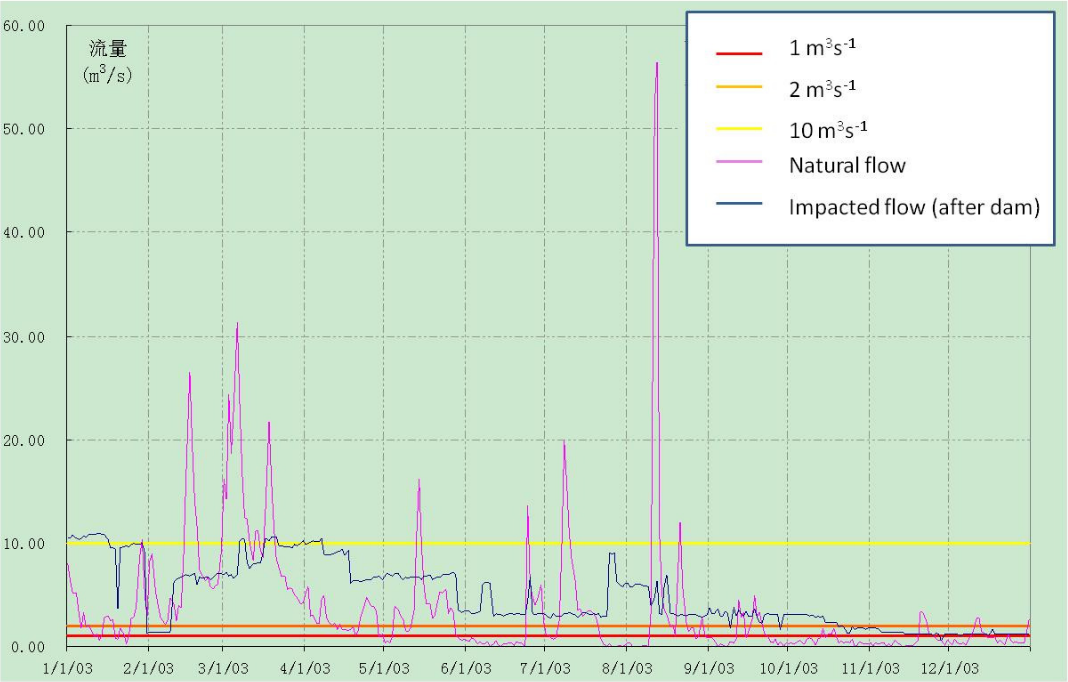

Figure 4 Natural flow and dam release flow at Miyan January 2003

The discharge at each hydraulic cross-section for a flow release from Jiaokou reservoir of 10 m^3s^{-1} was estimated by scaling the discharges recorded during the 2009 survey (Table 2). The results (Table 4) show that discharges would be insufficient at Miyan, Zhumei, Tianxiang and Jinxi cross-sections to create required velocity habitat for spawning of moonlight fish (0.5 ms^{-1}) given a release flows of 10 m^3s^{-1}. However, suitable velocities would occur at Maidong and Matan cross-sections.

Table 4 Discharge at cross-sections for a Jiaokou reservoir release of 10 m^3s^{-1}

	Cross-section name	Discharge (m^3s^{-1}) for release of 10 m^3s^{-1}	Discharge needed to achieve 0.5 ms^{-1} velocity (m^3s^{-1})	Discharge need met for moonlight fish spawning?
1	Miyan	10.0	42.91	X
2	Zhumei	3.3	69.77	X
3	Tianxiang	2.5	43.67	X
4	Jinxi	2.4	14.90	X
5	Maidong	3.2	1.34	√
6	Matan	1.6	1.26	√

Conclusions

Environmental flow requirements were calculated for the Zhangxi River based primarily on the flow needs of an indicator species, the moonlight fish. Flows required to provide suitable habitat for this species at different times of the year exceed the water requirements for other species and the water requirements to maintain water quality at the target standard. Results suggest that much of the Zhangxi River would provide suitable habitat for growth, refuge from large floods and over-wintering. However, only a few cross-sections would provide suitable spawning habitat for the current flow releases from Jiaokou reservoir.

To define fully the total flow requirements of the River, further research is required to estimate natural and impacted flows at various locations along the Zhangxi River and to determine flow needs to produce scour velocities sufficient to maintain deep pools.

Continued monitoring of the River is needed to test the findings of this research. The current work defines minimum flows and flow ranges. It is clear that ecological health of the River is likely to improve with higher environmental flow releases from Jiaokou reservoir. Future research should also work to define different classes of ecological health that result from different environmental flow regimes.

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