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Environmental flow allocation for the Zhangxi River, China

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Abstract

Ningbo city, located in Zhejiang province of 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 aimed at providing 400,000 m^3 of water per day to Ningbo from the upper reaches of the Zhangxi River by means of a cascade of reservoirs. A loan to support the work was agreed by the World Bank in 2005. Water resources management is achieved through operation of two major reservoirs, Jiaokou (completed in 1980, available storage capacity 75 million m^3) and Zhougongzhai (completed in 2006, available storage capacity 93 million m^3). Water is released from the reservoirs, via turbines to generate hydropower, to provide for the needs of 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 shows that it plays a very important role in the aspects of life, social activity, culture and leisure. Analysis of ecological monitoring data has 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. However, the River does not have abundant ecological resources.

This paper reports environmental flow needed to support key species in the river ecosystem quantified during an initial research project. It recommends a water allocation plan to meet the various water requirements of the ecosystem and local society in addition to Ningbo city.

Introduction

Adequate water is essential for human existence, including our health, growing our food, supporting our industries and maintaining ecosystems that provide 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 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. 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 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). 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

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

[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.

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.

In China, many scientists are now working on environmental flow and 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 flow in China. However, 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 definition of river healthy criteria is still under discussion, for example, each of the Yellow River Commission, the Yangtze River Commission, the Pearl River Commission has developed a healthy river indicator system. Many of the issues were debated at an open workshop at the Beijing World Water Congress, convened by the International Water Association in September 2006. 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) in Zhejiang Province was approved by a World Bank Board review in 2005 as a requirement for local economic growth. The NWEP includes a US$175 million component for the Ningbo Water Supply Project, which consists of a 400,000 m^3/d water treatment plant and 84 km of transmission mains. The source of water for the treatment plant is Jiaokou reservoir, 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, which is located approximately 15 km upstream of Jiaokou reservoir on the Zhangxi River and has an active storage capacity of 93 million m^3. The two reservoirs will be 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 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 average flow in Zhangxi River downstream of Jiaokou reservoir ranges from 4 m^3 s^{-1} during the winter to 20 m^3 s^{-1} in late summer. Current flows (after reservoir construction) were estimated to range from 2-4 $m^3 s^{-1}$, 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 house rare or endangered species, it does support a viable aquatic ecosystem including fish, invertebrates and plants that is 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.

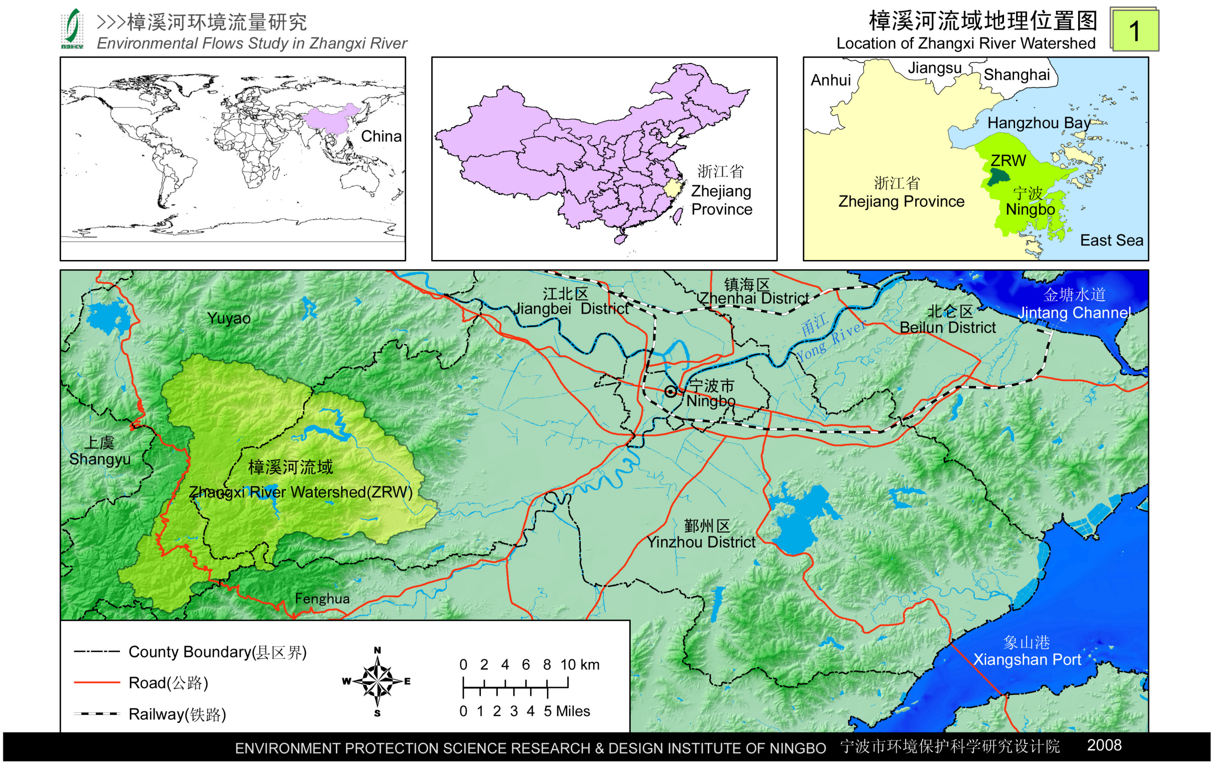

Figure 1 Location of Zhangxi River basin

The Zhangxi catchment

The Zhangxi River catchment is in the upstream of Yinjiang River which is a tributary of Fenghua River, located at transition between the Siming mountains and the coastal plain at the junction area of the three cities and counties of southwest Yin district, Fenghua and Yuyao county adjacent to Ningbo city (Figure 1).

Dajiao Brook and Xiaojiao Brook are two braches of Zhangxi River. Dajiao brook originates from Lianhua village, Shuangling hillock of Fenghua county, it flows through Tangtian, Daheng mountain of Yuyao county to Dayu of Yin district through northeast, and flows through Lijiakeng village, Zhougongzhai reservoir (Figure 2) to Miyan village and converges with Xiaojiao brook there. It is 44.9 km in total length and its drainage basin area is 168 km^2. Xiaojiao brook originates from Jinling within Yuyao county, it flows from Xiaoling, Shangzhuang, Lijiada to Zhongcun of Yin district, and flows from Xiaojiao, Tongjia to Miyan village and where it converges with the Dajiao brook. It length is 24 km and it drains an area of 91km^2. Dajiao Brook and Xiaojiao Brook converge in Miyan village at 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 2). The Zhangxi River flows throng Zhang village, Chang pool, Tianda rock, Zhongyang riverbank, Hencun pool, here it receives water from the Longguan brook and Heng brook, and then flows through Wutoumen pool and Zhongjiatan pool to Yinjiang town. It divides into two braches, one flows through Tashan weir to Yinjiang River, the other flows through Guangxi bridge, Hongshui bay to Nantang river which belongs to west Yin district river net.

Figure 2 The Zhangxi River catchment

Water demand assessment approach

Figure 3 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 consist of flows for 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 goes through the turbines and generates hydropower. 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 (Table 2), thus the water consumed is considered as the actual requirement of direct use (assuming that the quality of the returned water is sufficiently good to meet other demands).

Water requirements for local people vary slightly between years and are 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 the major requirement for water 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 is considered.

Analysis was undertaken of the flow needs of various elements of the ecosystem, based on available scientific knowledge and on information from local people and fishermen concerning the flow conditions under which different species have been found. The moonlight fish (*Distoechodon tumirostris*) was found to be the species most sensitive to flow in the Zhangxi River; it thus it has been adopted as an indicator of ecosystem health assuming that protection of habitat for this species will protect habitat for all river ecosystem components. These fish are characterised by their seasonal flow needs:

- high flows (giving velocities around 1 m^3s^{-1}) during spawning (April-May) – the high velocity and turbulence across the fishes body stimulates it to spawn.
- low flows (giving low velocities) during the growth of young (June-July) - the young fish have limited swimming ability
- refuge habitat during typhoon-generated floods (August-September) and
- deep pools for over-wintering (October-March).

The moonlight fish is potentially limited by physical habitat conditions that result from a combination of flow and channel geometry. It is recognised that floods have a dominant role in maintaining channel geometry, particularly deep pools in the river channel. To address this issue, six representative cross-sections were selected along the study reach downstream of Jiaokou reservoir. Measurements of depths and velocities were made at various flows to define hydraulic rating relationships for reach cross-section. This enabled the identification of minimum flows that would define threshold values of depth and velocity. According to our survey, suppose fish can survive in the downstream reach which just below Jiaokou reservoir , fish can survive in the whole downstream of Zhang Xi river. Only the cross section in the reach which just below Jiaokou reservoir is chosen as our representive cross section to explain the minimum environmental flow requirement of fish.

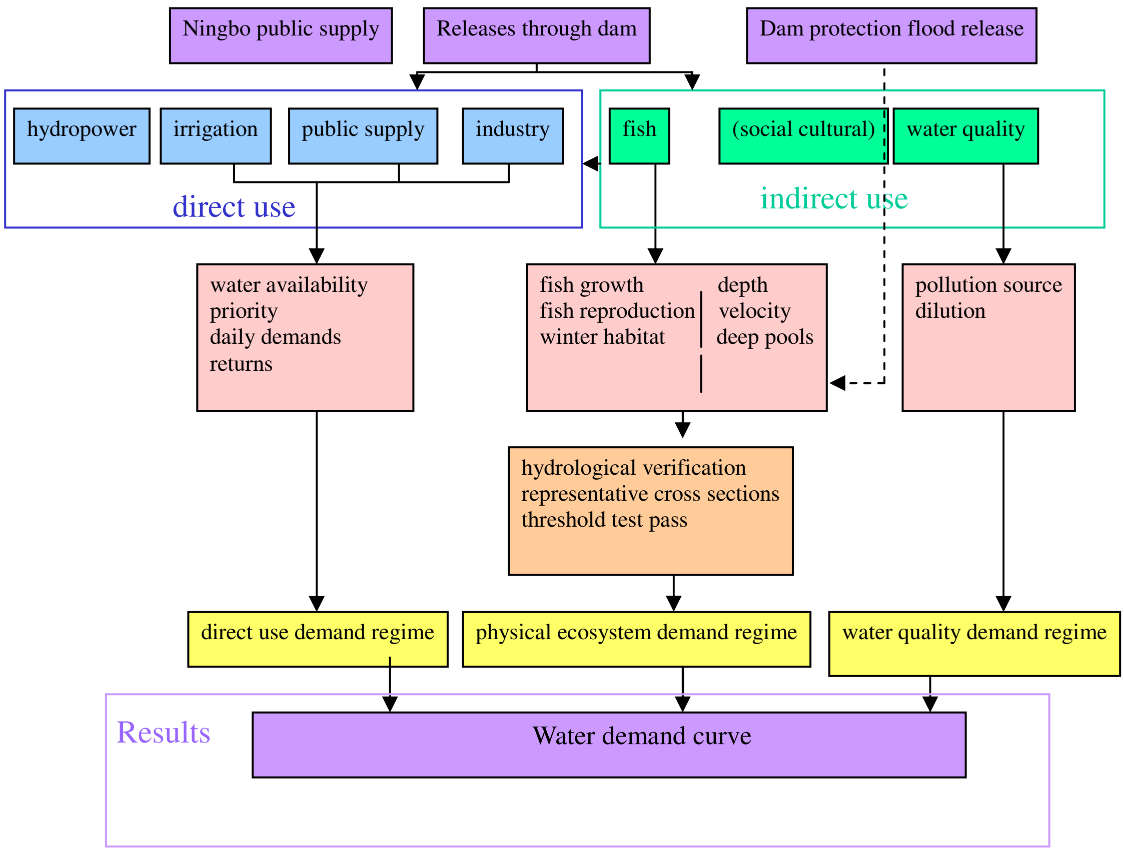

Figure 3. Schematic diagram of water demand assessment approach

National surface water quality standards have been set for China. Flow allocations for water quality were defined in terms of the flow needed to provide adequate dilution and to support bio-chemical processes to enable the river to meet Grade II of the standards. Domestic sewage is the main pollution source of Zhangxi River, which does not vary significantly in time, thus water requirements are assumed to be constant. Analysis of flow requirements, suggested that ensuring sufficient water for fish would also meet water quality, so no additional allocation was included for water quality.

As shown in Figure 3, the results of the water demand assessment approach are the combination of a series of demand regimes (direct, physical ecosystem and water quality) in the form of a water demand curve that defines the flow release needed from Jiaokou reservoir.

Analysis and discussion

Since direct water requirements can be readily calculated from available data without the need for new analysis, we focus here on the estimation of water requirements for water quality and fish.

Water requirements for water quality

Some 3,750 people live in the area along the Zhangxi River between the outlet of Jiaokou reservoir and Tashan weir downstream, 25,000 of them are residents of Zhangshui town and Yinjiang towns, as shown in Fig.3.The water waste discharged to the Zhangxi River varies between the towns and villages. The Chemical Oxygen Demand (COD) of village effluent is about 11 tonnes yr^{-1}, whilst COD of town effluent is about 146 tonnes yr^{-1}. NH_3-N of villages discharged to Zhangxi river is about 1.1 tonnes yr^{-1}, NH_3-N of towns discharged to Zhangxi river is about 11 tonnes yr^{-1}.

Around 8600 hectares of the riparian land is plough for arable cultivation during the dry season. We estimate that the overall discharge coefficient from farmland is CODcr 90 kg/ha/yr and NH_3-N 4 kg/ ha/yr. Assuming that 6% of this load is discharged to Zhangxi River, then the amount of agricultural pollution discharged amounts to CODcr 3.1 tonnes yr^{-1}, NH_3-N 0.14 tonnes yr^{-1} (Table 1).

Table 1 Pollutant discharged to the Zhangxi river (tonnes yr^{-1})

area \ Pollution source	domestic sewage		farmland source		industry source	
	COD	NH_3-N	CODcr	NH_3-N	CODcr	NH_3-N
the outlet of Jiaokou reservoir to Tashan weir	157	12.1	3.1	0.14	30	3.0

In this analysis we assume sufficient traverse mixing takes place in the river such that its chemical characteristics are homogenous within a cross-section and changes only occur along the water course; upstream-downstream. Thus water quality can be modelled by a one-dimensional approach as follows,

$$C(x) = C_0 \cdot e^{-Kx/u} \qquad \text{[Eq 1]}$$

u - the average velocity of the cross section,

K - the overall decompose coefficient of pollution,

C_0 - the concentration of pollution where x=0,

C(x) - the concentration of pollution where x=x.

Using the above model, it has been estimated that 1 m^3s^{-1} flow release from Jiaokou reservoir is sufficient to maintain the target water quality standards (grade II) in Zhangxi River under the current levels of pollutant discharge. At present a series of pollutant management controls are being implemented, particularly focused on reducing industrial effluent discharges. Additional measures are being developed to decrease urban domestic discharges. Consequently, it is envisaged that m^3s^{-1} flow will be more than adequate in future to maintain the target water quality.

Water requirements of fish

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. There are 10 fish species that exploit different habitat, including lotic fish and those preferring slow flow or still waters.

Numerous biological surveys have been undertaken along the Zhangxi River at key locations. Perhaps the most important species is the moonlight fish, which requires clean water and velocities in the range of 0-0.50 m s^{-1} for most of the year (Figure 4). Their fry/juveniles have no minimum flow requirement, but have limited swimming ability and so prefer slow velocities; they can survive high flows if slow flow refuge habitat is available. 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. 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. Hydraulic analysis demonstrated that the depth of water upstream of the weirs varied little with flow, whereas downstream depth was sensitive to flow change with significant depth only occurring during floods.

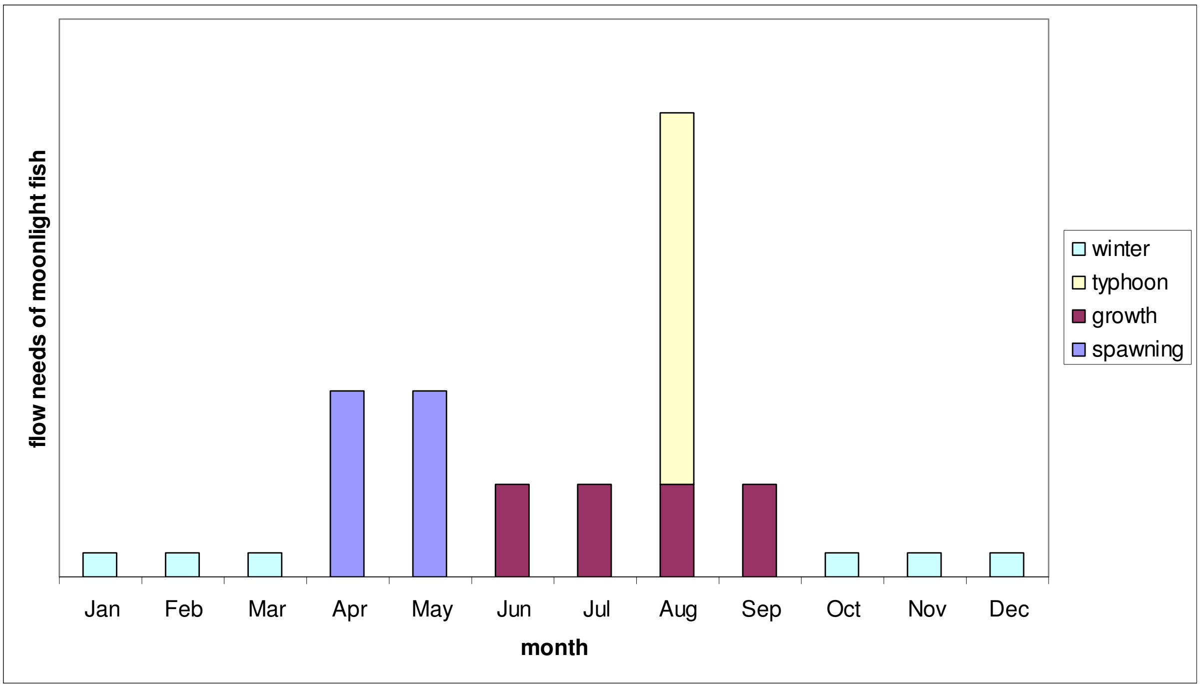

Figure 4 Indicative relative flow needs of the moonlight fish for different life stages

Slow velocity (<0.5 m s^{-1}) habitat for growth of young moonlight fish is abundant in the Zhanxi River, with a range of depths. shallow area and deep area with slow velocity to grow.

During the reproduction period (April-May) females are stimulated to spawn by fast flowing (0.5-1.5 m s^{-1}) shallow water. Hydraulic analysis showed that the lower threshold to produce spawning habitat was when the release flow of Jiaokou reservoir is 2 m^3s^{-1}; better and more widely occurring spawning habitat occurs when the release flow is 10 m^3s^{-1}. During the spawning period((April-May), it is enough for fish only if the release flow can meet 2-10 m^3s^{-1} for 1-2 days per week.

Analysis of modelled natural flow data (before reservoir construction) showed that suitable spawning flows (2 to 10 m^3s^{-1})can be met in most years. And after running of Jiaokou reservoir, the release flow from Jiaokou reservoir can also met the spawning flows in the driest year of 2003. Figure 5 shows that after construction of Jiaokou reservoir, the minimum flow of Zhangxi River is enhanced, while the maximal flow is reduced, this is good for the reproduction of fish, but it is bad to shape the location for refugee and deep pool. Further analysis confirmed that 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. However, it was recognised that major floods are still required to maintain the deep pools. Whilst the Zhougongzhai and Jiaokou reservoirs can attenuate flood discharge, they cannot eliminated floods entire, especially those resulting from high intensity storms during typhoons in August and September.

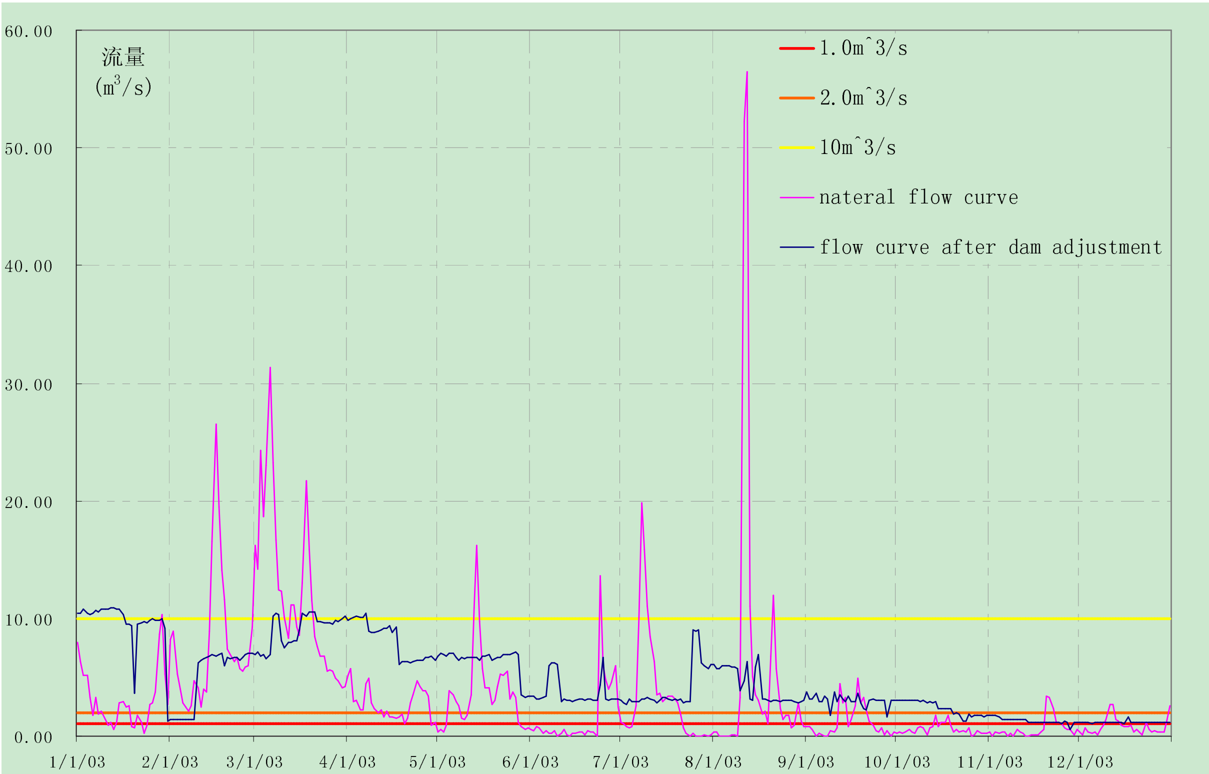

Figure 5 Natural Flow and Release Flow after Dam Operation

No other organisms were identified that had more stringent flow requirements than the moonlight fish. Consequently, it was considered that other species would survive if suitable conditions were provided for this indicator fish.

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.

The overall minimum flow needs of the Zhangxi River, and thus the releases from Jiaokou reservoir, results from the addition of the environmental flow for the moonlight fish and the consumptive use of water requirements for public supply, agriculture and industry. These figures are given in Table 3.

To define the total flow requirements of the River, wee need to add the flows needed to produce scour velocities sufficient to maintain deep pools. This is not currently known and will require further research.

Continued monitoring of the River is required 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.

Acknowledgements

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Table2 Direct water requirement of Zhangxi River catchment (m^3/d)

	January	February	March	April	May	June	July	August	September	October	November	December
water for agriculture					12000	12000	12000	12000	12000			
water for villages	150	150	150	150	150	210	210	210	210	150	150	150
water for industy	180	60	180	180	60	60	60	60	60	60	60	60
water for Longguan town	400	400	400	400	400	400	400	400	400	400	400	400
water for Zhangshui Town	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
water for Yinjiang town	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800
water for Zhenhai power plant	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000
subtotal	19530	19410	19530	19530	31410	31470	31470	31470	31470	19410	19410	19410

Table 3 Direct and indirect flow requirement of Zhangxi river (m^3s^{-1})

	January	February	March	April	May	June	July	August	September	October	November	December
direct water requirement	0.0023	0.0022	0.0023	0.0023	0.0036	0.0036	0.0036	0.0036	0.0036	0.0022	0.0022	0.0022
water to maintain the water quality	≥1	≥1≥	≥1	≥1	≥1	≥1	≥1	≥1	≥1	≥1	≥1	≥1
water for fish	≥1	≥1	≥1	≥1，At least one day the flow reaches to 2-10 in 7 days		≥1	≥1	≥1	≥1	≥1	≥1	≥1
overall water requirement	≥1	≥1	≥1	≥1， 2-10 At least one day the flow reaches to 2-10 in 7 days		≥1	≥1	≥1	≥1	≥1	≥1	≥1

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