<u>CONCEPT PAPER</u>

REOPTIMIZATION OF XIAOLANGDI DAM ON THE YELLOW RIVER

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The Natural Heritage Institute

Background on the Yellow River:

The Yellow River is the second longest river in China. It flows 5,464 kilometers from the Tibetan plateau in Qinghai to the Bohai Sea in Shandong province, through a catchment of about 795,000 km2. It is traditionally divided into the upper reach (above Hekou); middle reach (between Hekou and Huayuankou, or Taohuayu); and lower reach (below Huayuankou, or Taohuayu). It carries just 2.6% of the natural runoff of the entire country (annual mean of 58 billion m3), yet nourishes 12% of the country's population, irrigates 15% of the country's arable land, and is the source of water supply to more than 400 cities and towns along its banks.

The river is fed by melting glaciers and snow pack in the spring and monsoon in the summer. Historically, the river has been very flood prone. Records dating back 2540 years reveal that the Yellow River had burst its banks or overflowed 1590 times.

But today, these large flow events are contained by 10 large dams on the mainstem (plus over 3100 smaller reservoirs throughout the basin with a total storage capacity of over 58 billion m^3) and a levee system that confines the river for almost its entire length to the sea. Those levees confine the flood events to a portion of the historic floodplain that is actually quite wide, some 24 kilometers in some places, and that is made necessary by the elevated river bed, which is often over 10 meters above the floodplain. The reason is that the Yellow River carries (and deposits) more sediment than any other large river. By volume, half of the flow of the river through the middle and lower reaches is composed of sediment. This amounts to some 300 to 400 million tons of sediment deposited in the lower reach of the Yellow river every year, which also creates and ever-growing delta at the mouth.

These dams and diversions have dramatically reduced both water and sediment flows over the past 50 years, by about 5 fold measured at the mouth of the river, and seasonal peak flows have been almost entirely lost. Until recent years, the river frequently did not reach the sea for much of the year. Today, a minimal (50 m^3/sec) baseflow is maintained.

These physical changes in the river have also caused profound changes in its biota. Plankton production has always been rather poor in the Yellow River, yet, in the 1950's the river supported a large fishery. In recent years, however, the fishery has declined from 8 million kg/year in 1950's to 0.01 kg/year today, an astonishing collapse. The number of fish species has also declined from 152 in the 1950s to 47 today. Over half of these remaining species inhabit the lower reach below Xiaolangdi dam. The composition of the fish species has also changed greatly, with the number of nationally protected species, endangered species and indigenous species reduced. Today, it is difficult to find the traces of native fish; while invasive and artificially bred fish are comparatively abundant.

Compared with 1986, the total area of wetlands of Yellow River decreased by 16.36%, and the swamp wetlands decreased by 27.53% by 2006. At the same time, the structure of wetlands also changed. The area of natural wetlands decreased and artificial wetlands increased (by 25.34%). Yet the situation at the mouth is much worse. There was a decrease in the Yellow River delta wetland area of about 60% from 1984 to 1996.

For a long time, development of the Yellow River has focused primarily on flood control and agricultural and industrial water supply, and ignored ecological issues. As the economy and society developed, conflicts among different users of the Yellow River's water resources have become increasingly prominent, and the river's ecosystem is threatened by multiple stresses. The Yellow River Conservation Commission (YRCC) is aware of the need to restore the flow regime in the Yellow River, particularly the lower reach, for three purposes:

- Maintain the stability of the river channel
- Protect fishes and other aquatic species
- Reconnect the wetlands to the river

This proposed project addresses the potential for reoptimizing the operations of Xiaolangdi dam, which controls flows through the ecologically important lower reach all the way to the sea, to generate the needed environmental flows.

Background on Xiaolangdi Dam:

Xiaolangdi reservoir is located at the end of the middle reach of the Yellow River, 130km downstream of the Sanmenxia reservoir and 128 km upstream of Huayuankou. It has a total capacity of 12.65 billion m3, in which the sediment deposit storage is 7.55 billion m3 and the long-term effective storage capacity is 5.1 billion m^3. Mean annual inflow to the reservoir is 27.9 billion m^3 and average annual sediment deposit is 1.3 billion tons. The Xiaolangdi Project started storing water on October 25, 1999; the first unit generated electricity for the Henan provincial power grid on January 9, 2000; the project was completed at the end of 2001.

Xiaolangdi is a multipurpose project. The main objectives are flood control (including ice jamming prevention) and siltation reduction. It is the key project for controlling the flood and the sediment in the lower reach of the Yellow River. Its secondary purposes are water supply, irrigation and power generation. Xiaolangdi provides irrigation water to some 100 water districts outside of the levee system. The YRCC operates Xiaolangdi Reservoir for water regulation and the Henan Power Grid is responsible for power generation. Xiaolangdi Dam Project Construction and Management Bureau (XDPCMB) is responsible for coordinating between water regulation and power generation, operating flood control facilities, and meeting the flow targets set by YRCC for average daily discharge, minimum flow rates, and sediment transport. YRCC requires that the average daily discharge cannot have an error larger than 5%.

The Xiaolangdi project was mainly designed for these purposes rather than for environmental benefits. However, the operation of the project is also the key to ecological maintenance of the lower Yellow River because it controls the flows into the estuary and delta at the Bohai Sea.

Ecological Management Challenges in the Lower Yellow River:

The major issues that impact the ecological health of the lower Yellow River include declining water availability, sedimentation of the channel, reduction in extent and quality of riverine wetland and degradation of water quality.

Starting from the 1970s, well before Xiaolangdi was constructed, the river often dried up before it reached the sea. This occurred in 20 of the 26 years between 1972 and 1997, and the dry section grew longer every year. At its maximum, the total length of the dry up was of 683km. The duration of the dry up also became longer every year, resulting in accelerated shrinkage of the river bed. In 1997, it lasted for 226 days. As a consequence, the Yellow River Delta was deprived of silt as well as water inflow, leading to a gradual 60% reduction in the areal extent of the wetlands from 1984 to 1996, a falling groundwater table, sea water intrusion and accelerated salinization of the soil. The ecological integrity of the delta and estuary were seriously damaged, causing severe negative impact on the social and economic development of the lower river basin.

As a result, fish populations have decreased to 40% of historic levels for the national fish Cyprinus (Yellow river carp) and coilia ectenes (the estuarine tapertail anchovy). Adding to these woes, the Xiaolangdi hydropower plant is operated mainly for peak power generation. Because of that, daily fluctuation of the water release downstream is relatively large, resulting in negative impacts on water supply and a greatly altered flow pattern downstream of the dam.

Yellow River Management Policy Framework:

In response to concerns about the declining health of the Yellow River and to reverse the growing problems of river drying up, siltation, pollution, and ecological degradation, Li (2004) formulated a policy framework for management of the Yellow River. The policy framework has remained the fundamental guide to managing the Yellow River by the YRCC.

The framework has four levels:

- a vision statement
- four overarching objectives
- nine action strategies
- three approaches to understanding the river

The vision statement for the Yellow River, or the "ultimate target," is "Keeping the Yellow River Healthy". The vision encompasses both ecological health and social-economic health, which can be expressed as the total amount of water resources, flood discharging capacity, sediment-carrying capacity, self-purification capacity, and the capacity to maintain ecosystems (Li 2004).

The four overarching objectives (or criteria) expressed as negatives, or the outcomes that are undesirable are known as the "four no's"

1. no embankment breaching
2. no river running dry
3. no water pollution beyond standard
4. no river bed rising further.

The nine actions strategies were devised to tackle the main identified problems in the yellow rivers are (Li, 2004):

1. Take measures to reduce sediment inflow to the Yellow River.
2. Manage water resources utilization of the Yellow River basin and its related regions effectively.
3. Strengthen the study on water transfer plans to increase the water resources of the Yellow River.
4. Establish a water-sediment discharge regulation (WSDR) system.
5. Work out a scientific, and reasonable, general plan for controlling and managing the lower river course.
6. Create favourable hydrological processes to mitigate the shrinking of the main channel.
7. Meet water demands to maintain river's natural cleaning capacity.
8. Manage the Yellow River Delta to reduce seawater impact to the lower reach.
9. Maintain the ecological system sustainable in the Yellow River Delta.

Ecological Management Initiatives at Xiaolangdi:

With guidance of the above policy framework, YRCC has instituted gradual changes in the operation of the Xiaolangdi dam under the guidance of policy framework. Since 2002, YRCC has operated the dam to release some 14 million m3 of water for artificial floods to improve both water and sediment flows through the delta to meet the following objectives:

- Flush the river sediments
- Restore the floodplain and delta wetlands
- Improve river morphology and reduce flood risk

Since the operation of the Xiaolangdi Dam, drying up in the lower reach has been eliminated. Also since then, the lower Yellow River has not had any years of total loss of flows, which has helped restore some of the destruction done to the Yellow River wetlands in the last century. The area of freshwater wetlands in the Yellow River Delta has significantly increased and the health of the ecosystem has been stabilized, playing an important role in maintaining the health of the Yellow River.

As of October 2009, YRCC has made releases from the Xiaolangdi reservoir for water and sediment flow improvements nine times. Seven out of those took place in the later half of June. These artificial peak floods were released to scour the river bed downstream. In all those nine times, the largest instantaneous flow rate was 4280 m^3/s, the largest average daily flow rate was 4040 m^3/s, the total amount of water released downstream was estimated to be 34.2 billion m^3, the amount of sediment that was flushed from the bottom of the Xiaolangdi reservoir was 250 million tons, the amount of sediment scoured from the river bed downstream was 300 million tons, and the total amount of sediment carried into the sea was 550 million tons. On average, the elevation of the river bed was reduced by 1m. The minimum river channel capacity was increased from 1800 m^3/s in 2002 to nearly 4000 m^3/s after the flood period in 2009. The siltation and channel shrinkage problems in the lower Yellow River were effectively controlled.

In 2008, YRCC declared a policy to change tradition reservoir operations to improve ecological functions, recognizing that preserving the ecological functions in the future will be key to maintaining the health of the Yellow River. Some remarkable results of these operational improvements have been achieved:

- Rare fishes, such as saury and bronze guodge, have reappeared
- New habitats for birds have increased, resulting in an increases in species from 187 in 1992 to 283 in 2004
- The number of rare wild animal species in the basin's preserves has nearly doubled to 459

Although the Xiaolangdi ecological restoration has had significant results, YRCC recognizes that reservoir operation to improve ecological functions is complex and there are still problems to be addressed, mainly:

- The environmental flow requirements for the aquatic species and their ecosystems in the river delta and wetlands are still not well understood. In response to this, many environmental flow assessments have been undertaken on the lower Yellow River, using a range of methodologies. The most recent and comprehensive of such studies was the one conducted by Gippel et al. (2012) and funded by the AusAID. Several experts from YRCC have participated in this study.
- Reoperation of Xiaolangdi has been limited to the macro levels, such as keeping continuous flow in the lower Yellow River and controlling sediment downstream. Re-establishing a more naturally variable flow pattern into the estuary and delta has still not been accomplished.

Thus, the objectives of the ecological restoration so far have been too narrow and the targets are too coarse. A more in-depth study of the ecosystem and its changing processes, the elements of a healthy Yellow River, and refined ecological targets are needed to guide the reservoir's ecological restoration.

The Reoptimization Concept:

The more appropriate reoptimization objective is to restore a more naturally and seasonally variable flow pattern below Xiaolangdi all the way to the sea to:

- reconnect the river to its floodplain <u>within</u> the existing levee system,
- increase the areal extent, duration and frequency of seasonal inundation of the wetlands in the delta (under the assumption that that flow pattern will also benefit the upstream wetlands)
- provide a magnitude, frequency, duration and timing of both high and low flows that would be most beneficial to native fish species, including pelagic, estuarine, anadromous, and catadromous species
- assure a continuous flow to the sea year round without diminishing current benefits that Xiaolangdi reservoir is providing, which include:
    - reduction of flood risks to people and property (although this may require relocation of some vulnerable populations to locations outside of the levees)
    - sediment flushing
    - power output (although some rescheduling of power generation may be necessary)
    - irrigation water supplies

Indeed, the reoptimization analysis will explicitly seek to enhance all of these benefits, as described below.

To understand the reoptimization concept, let us first review the current operations. At present, Xiaolangdi releases water from storage in anticipation of the summer monsoon season to create flood reservation and also during the monsoon season as necessary to prevent overtopping of the dam. Yet, these flood control operations have not prevented some villages within the levee system in Shandong Province from being flooded in some years. These releases also flush sediment and partially inundate the wetlands. This water is lost to irrigation, however, and in extreme cases, must bypass the powerhouse, resulting in a loss in power generation.

Also, under current operation, irrigation water is released from Xiaolangdi all year around to some 100 water districts outside of the levee system, irrigating about _____ hectares of land. Diversions from the river below the dam occur at many places, but are restricted during times when sediment is being flushed. This surface water is supplemented by groundwater pumping, which occurs in all years. This has resulted in cones of depression in the groundwater table in the northern part of the irrigation command area. In most areas, the groundwater is replenished only through rainfall infiltration and seepage from the river. In ____% of years, some field is fallowed because of insufficient water supplies. Power is generated opportunistically as water is released from the dam for these other purposes. This power is ____% of the entire power generation in the Henan and Central China power grids.

Under the reoptimization concept, the storage levels in Xiaolangdi going into the monsoon period would be lowered, compared to current operations, by delivering some of that water to the irrigation districts that also use groundwater. These districts would use this surface water instead of pumping the groundwater, or some of this surface water would be used to actively replenish the aquifers. The result in either case would be higher groundwater levels in the areas that have a depressed groundwater table. The increase in groundwater storage would allow the groundwater to substitute for some portion of surface water deliveries in drier years. This would improve the reliability of irrigation water supplies and prevent fallowing, and it would increase the amount of water in Xiaolangdi reservoir in these drier years.

The increased capacity to store flood waters would have two benefits: (1) less water would need to be released for flood control during the monsoon season, resulting in an increase in stored water, and (2) the risk of unintentional flooding in the populated areas would be diminished.

Improved environmental flows would be achieved by the optimization in the following way: Xiaolangdi and its associated irrigation system would have additional water in storage from two sources: (1) the additional flood waters that it is able to capture, and (2) the improved groundwater storage that can be used instead of reservoir releases. Some of this additional water can be used to improve environmental flows by releasing it to augment peak flows coming in from the downstream tributaries during heavy rain events. This can create the magnitude and duration of flows needed to inundate the wetlands at the mouth of the river (and also flush sediment to the sea). These environmental flows can also be shaped and timed to provide the maximum benefit to the native fish species.

But these larger environmental flows are also controlled flood pulses designed to inundate portions of the leveed floodplain. This may inundate farmland and structures in this floodplain, which has a population of some 1.8 million inhabitants. Therefore, it will also be necessary to "floodproof" the floodplain by relocating the homes and other vulnerable structures to higher ground, perhaps outside of the levees. The farmland is less of an issue if it is planted to seasonal crops, because the inundation will be temporary and probably beneficial since it will bring nutrients and soil moisture to these farms. Permanent crops are a larger concern because they may not be compatible with the desired inundation. The reoptimization study will determine the location and extent of the conflicts between current land uses and desired environmental flows and develop a strategy for mitigating them.

This reoptimization plan that will emerge from this investigation will satisfy all of the objectives recited above: improved ecosystem functions, improved water supply reliability, and reduced flood risks. The study will also explore how the reoperation of Xiaolangdi reservoir will make the lower Yellow River more resilient to global climate change. The expected effects will be that the hydrologic extremes will become greater. Thus, the floods will be larger and more frequent, and the droughts will be more severe and last longer. For both of these, the engineering solution is to create more storage to capture the larger floods and buffer the droughts. That is exactly what the reoperation plan for Xiaolangdi will do – create additional flood reservation and additional water supply.

Gippel et al. (2012) found that in the lower Yellow River, water availability is a major limitation for environmental flows. In their study, Gippel et al. (2012) define flow objectives for each of the environmental assets (water quality, geomorphology, fish, birds, macroinvertebrates and vegetation) in the lower Yellow River, and based on those environmental flow objectives, recommend a number of environmental flow options, each with a different volume of water that is likely to result in a particular degree (or state) of river health in a particular reach. These recommendations will be adopted as the environmental flow requirements in this reoptimization study. Please see Appendix A for a summary of the recommended environmental flow options by Gippel et al. (2012).

The study workplan:

The tasks contemplated for the reoptimization study are:

1. Map the habitat areas to be restored in the floodplain (within the levees) and in the delta.
2. Determine the environmental flow requirements that would restore those habitat areas based on the assessment by Gippel et al. (2012).
3. Evaluate the floodplain land uses that would be impacted by the desired environmental flow requirements.
4. Develop an impact avoidance, mitigation or compensation strategy for these impacts, and modified the environmental flow requirements as needed.
5. Make an operation schedule that would fulfill the environmental flow requirements from Task # 4.
6. Using existing (or enhanced) dam operation models, quantify the extent to which the change in dam operations would affect water supply and power generation benefits.
7. Consistent with the environmental flow reoperations identified in Task # 4, study and design the conjunctive groundwater/surface water management arrangement described in this concept paper and quantify the improvement in irrigation water supply reliability that would result.
8. Consistent with the environmental flow reoperations identified in Task # 4, evaluate how the changes in the scheduling of power output from Xiaolangdi can be offset by changes in the power generation schedule for other power plants in the Henan Province and Central China Power Grids.

9. Re-run the analyses in tasks 6-8 assuming a range of reasonable values for the probable hydrologic effects of global climate change.

10. Re-run the analyses in tasks 6-8 assuming a range of reasonable values for the probable hydrologic effects of the South-to-North diversions from the Yangtze River into the Yellow River.

11. From the foregoing tasks, develop a reoptimization plan for Xiaolangdi that assumes a mid-range value for the effects of climate change and the South-to-North diversions. .

12. Evaluate the costs and benefits associated with the reoptimization plan, and adjustments necessary to assure that the reoptimization plan is economically feasible.

13. Develop a monitoring plan to evaluate the effect of the reoptimization plan on all relevant parameters.

14. Conduct a trial implementation of the reoptimization plan and monitor the results.

15. Adjust the reoptimization plan as necessary to achieve the project objectives.

16. Feed the results and lessons learned in the global learning process, together with results from all the other demonstration sites in China, Africa, India and Latin America, and widely disseminate.

Appendix A. Recommended Environmental Flow Options from Gippel et al. (2012)

In the environmental flows assessment carried out by Gippel et al. (2012), the lower Yellow River was divided into four reaches (shown in Figure A1). The reaches were:

Reach 1- Xiaolangdi to Gaocun

Reach 2- Gaocun to Taochengpu

Reach 3- Taochengpu to the estuary

Reach 4- Estuary to Bohai

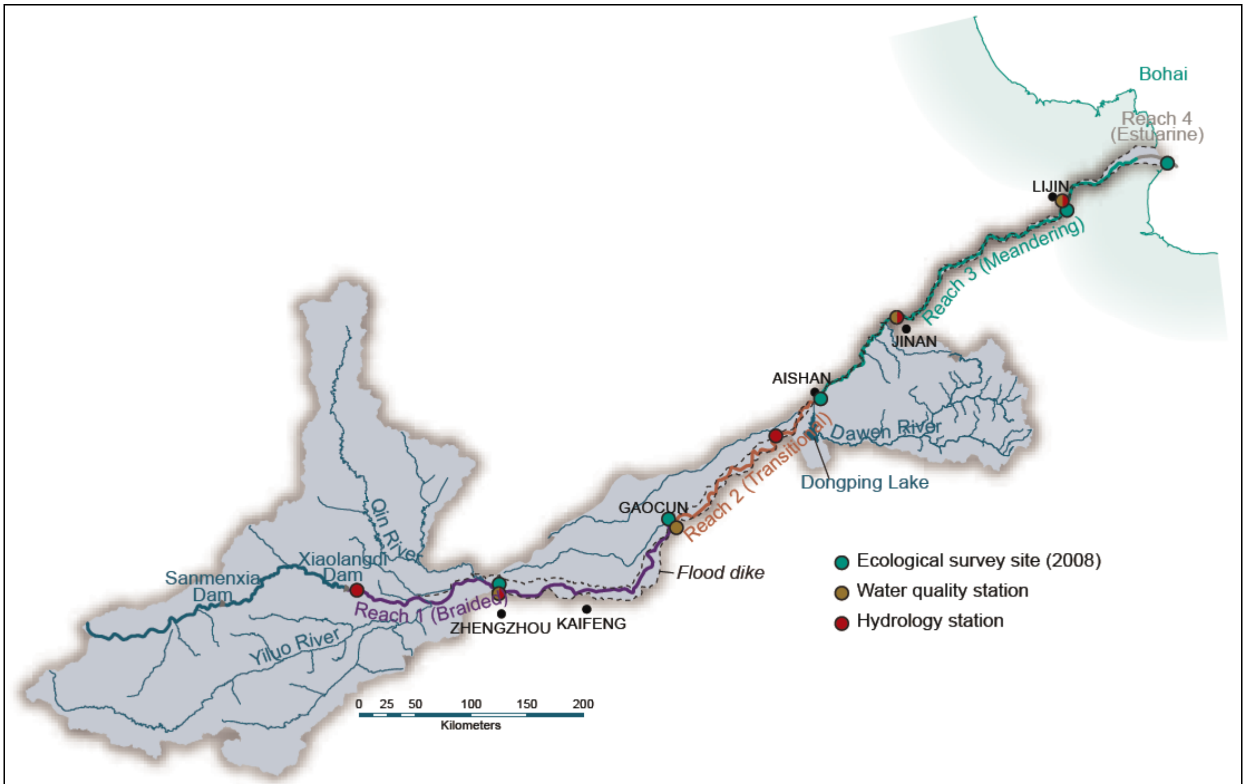

Figure A1. Lower Yellow River, showing four reaches used in environmental flow assessment, and location of gauging stations used for water quality and hydrological analysis

The environmental flow objectives for the lower Yellow River that were specified by Gippel et al. (2012) are grouped into six categories:

- Geomorphologic objectives
- Water quality objectives
- Waterbird objectives

- Fish objectives
- Macroinvertebrate objectives
- Vegetation objectives

Tables A1 to A7, extracted from Gippel et al. (2012), list those objectives. A set of low-risk and a set of medium risk envionmental flow options are recommended for each of the above objectives. Tables A8 to A15 show those environmental flow options.

Table A1. Geomorphologic-based objectives and flow requirements

No.	Objective	Flow component	Hydrologic criteria	Mean annual frequency/ duration	Inter-annual frequency	Timing	Reach	Reference
G1	Scour and deposition processes to maintain dynamic and diverse habitats in the channel and connected floodplains	Bankfull	2600–4000 m^3/s	≥ 1 per year / ≥ 1 day* duration	≥4 in 5 years	Jun–Sep	Reach 1	Richards et al. (2002)
G2	Maintain channel capacity at 4,000 m^3/s	Bankfull	2600–4000 m^3/s	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun–Sep	All reaches	Liu et al. (2006)
G3	Seaward progradation of the delta	Bankfull	Sediment load >3.45 × 10^8 tonnes at Lijin; event mean sediment concentration ≥ 35 kg/m^3	≥ 1 per year	≥4 in 5 years	Jun–Sep	Reach 4	Wang K et al. (2007); Wang et al. (2010)
G4	Flow into delta wetland channels to maintain channel form (and also provide freshwater and nutrients to the delta wetlands)	Bankfull	>3,000 m^3/s to allow gravity flow	≥ 1 per year / ≥ 10 days* days duration (or as required)	≥4 in 5 years	Jun–Sep	Reach 4	Jiang Xiaohui (YRCC, pers. comm., November 2010)

* Based on expert opinion; refinement of this criterion will require investigation.

Table A2. Water quality-based objectives and flow requirements

No.	Objective	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing	Reach
WQ1	Dilute contaminants to Grade III standard	Low flow and high flow	≥ 320 m3/s	≥ 90% of time	≥ 75% of the time	All year	Reach 1
WQ2	Dilute contaminants to Grade III standard	Low flow and high flow	≥ 234 m3/s	≥ 90% of time	≥ 75% of the time	All year	Reach 2
WQ3	Dilute contaminants to Grade III standard	Low flow and high flow	≥ 146 m3/s	≥ 90% of time	≥ 75% of the time	All year	Reach 3
WQ4	Dilute contaminants to Grade III standard	Low flow and high flow	≥ 60 m3/s	≥ 90% of time	≥ 75% of the time	All year	Reach 4
WQ5	Temperature within range of tolerance of biota, especially fish spawning	Low flow, high flow, pulses and bankfull	As required (see fish objectives)	≥ 90% of time	≥ 75% of the time	All year (esp. May-Aug)	All reaches
WQ6	Total suspended solids concentration within range of tolerance of biota, and within pre-dam range	Low flow, high flow, pulses and bankfull	WSDR event peak ≤ 110 kg/m3 (g/L)	≥ 90% of time	≥ 75% of the time	June-Aug	All reaches

(WSDR = water sediment discharge regulation)

Table A3. Waterbird-based objectives and flow requirements

No.	Objective	Flow component	Hydrologic/hydraulic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing	Reach
B1	Foraging	Low flows	Expose *Carex*	Continuous	≥ 75% of the time	Nov–mid-Mar	Reaches 1 and 4
B2	Foraging	Low flows	Shallow water (<0.3 m) over submerged or emergent aquatic plant community with mud or sand base	Continuous	≥ 75% of the time	early-Oct –Feb	Reaches 1 and 4
B3	Foraging	Low flows	Expose mudflats	Continuous	≥ 75% of the time	Mar–Jun; Nov–Jan	Reaches 1 and 4
B4	Wintering area	Low flows	Maintain ice free water bodies*	Continuous	≥ 75% of the time	Dec–Feb	All reaches
B5	Food supply and breeding	High flows	Inundate areas of submerged macrophytes (*Vallisneria*, *Phragmites*, *Typha*, *Carex*, *Tamarisk*)	Continuous	≥ 75% of the time	Jul–Oct	All reaches
B6	Foraging	High-flow recession	Gradually receding water levels from Bankfull peak	Continuous	≥ 75% of the time	Sep–Nov	All reaches
B7	Mudflat foraging habitat creation	Bankfull	An annual event that supplies enough sediment load to at least maintain delta area	≥ 1 per year / ~10 – 30 days duration	≥ 4 in 5 years	Jul–Oct	Reach 4
B8	Summer–autumn habitat area	Bankfull	An annual event to inundate backwaters and wetlands	≥ 1 per year / ≥ ~5 days duration	≥ 4 in 5 years	Jul–Oct	All reaches

* The lower Yellow River is naturally prone to freezing over in the lower reaches in winter. Freezing is routinely managed by YRCC to prevent ice-flood, so this is considered a passive objective that does not require active implementation.

Note: These objectives are the key requirements, simplified from the full suite of flow–waterbird relationships.

Table A4. Fish-based objectives- relevant species and functions

No.	Objective	Relevant species	Function
F1	Maintain low flow habitat continuity through perennial flow	All species	Habitat maintenance
F2	Maintain shallow habitats with moderate-high velocity for shallow water dwelling species, and spawners during low flow periods	Northern bronze gudgeon; Yellow and ussuri catfish	Resident habitat and/ or spawning habitat
F3	Facilitate downstream migration of diadromous species by allowing free passage	Saury; Japanese eel	Life cycle/ migration requirement
F4	Maintain sufficient water depth in pools for large bodied fish	Big head carp and grass carp; Barbel chub; Chinese perch	Habitat maintenance
F5	Stimulate spawning, migration (anadromy and potadromy) and maintain habitat continuity between near-shore/estuarine and freshwater habitats to allow free upstream passage; inundate high flow backwaters and river associated wetlands	Northern bronze gudgeon; Saury (anadromy); Yellow River carp, big head carp and grass carp; Barbell chub (potadromy)	Spawning, spawning migration (upstream)
F6	Provide suitable habitats for spawning, and the development and recruitment of early life history stages by allowing access of large bodied fish to backwater and wetland habitats with abundant submerged vegetation	Saury (anadromy); Yellow River carp, big head carp and grass carp; Barbel chub (potadromy)	Spawning, embryonic development and larval-juvenile recruitment
F7	Maintain downstream transport of semi-buoyant eggs within the water column	Big head carp and grass carp; Barbel chub (potadromy)	Egg development and downstream transport
F8	Maintenance of appropriate salinity gradients in estuarine reach during spring for anadromous spawning migration	Saury; Japanese eel	Life cycle/ migration requirement
F9	Maintain sufficient water depths in pools and wetlands for large bodied fish	Japanese eel, Yellow River carp, big head carp and grass carp; Barbel chub (potadromy)	Adult habitat
F10	Maintain permanent/regular, low water velocity habitats with abundant submerged/emergent vegetation and/or fine sediments in river associated backwaters and wetlands for small bodied species	Sharpbelly and Cobitids	Habitat
F11	Maintain productivity (phytoplankton, zoobenthos, calanoid copepods) in lower riverine reaches and the estuary	Estuarine dependents and migratory species; Mullets; Chinese perch; Asian Goby	Estuarine productivity
F12	Maintain low velocity littoral habitats for small bodied species, particularly Cobitids	Spined and Oriental weather loach	Adult habitat
F13	Maintain shallow pool crossings with moderate-high velocities and coarser substratum (sands)	Northern bronze gudgeon; Big head carp and grass carp; Barbel chub	Habitat
F14	Maintain submerged aquatic vegetation, e.g. *Vallisneria*, *Potomageton* and *Myriophyllum* spp.	Big head and grass carp; Barbel chub; Spined and Oriental wheather loach	Habitat
F15	Maintain aquatic emergent vegetation, e.g. *Phragmites* and seasonally submerged meadow vegetation	Big head and grass carp; Barbel chub; Spined and Oriental wheather loach	Habitat
F16	Maintain minimum 2 mg/L dissolved oxygen, particularly in deeper pools	all	Habitat
F17	Maintain unconsolidated soft-bottom, substrates in estuarine backwaters and tributaries	Estuarine dependant species (*Synechobius ommaturus*)	Habitat
F18	Maintain sediment scour, tidal flushing and associated salinity dynamics to support estuarine dependant species	Estuarine dependent, catadromous and anadromous species	Habitat

Table A5. Fish-based objectives- flow specification and relevant reaches

No.	Flow component	Hydraulic/hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing	Reach
F1	Cease to flow; Low flow	Q ≥ YRCC warning standards of low flow emergency; maintain area‡ ≥ critical depth* at pool crossings (specified each month)	Continuous	≥ 75% of the time	All year	All reaches
F2	Low flow	Maintain area‡ ≥ critical depth* with V ≤ 2.0 m/s[1,2]	Continuous	≥ 75% of the time	All year	Reaches 1– 3
F3	High flow, high-flow recession	Maintain longitudinal connectivity and area‡ ≥ critical depth* over barriers (shallow areas)	Continuous	≥ 75% of the time	Jul-Oct	All reaches
F4	Low flow	Maintain area‡ with depth ≥ critical depth* in pools	Continuous	≥ 75% of the time	Nov-Mar	Reaches 1– 3
F5	High-flow pulse	Achieve area‡ with depth ≥ critical depth* over barriers (shallow areas)	≥ 1 per year / 10 – 20 days[1]	≥ 4 in 5 years	Apr-Jun	All reaches
F6	High flow	Maintain area‡ with D = 0.5 – 1.0 m[1,2] and V ≤ 1.4 m/s[1,2]	Continuous	≥ 75% of the time	Apr-Sep	All reaches
F7	High flow	Maintain area‡ with velocity 1.0 – 2.0 m/s[1]	Continuous	≥ 75% of the time	Apr-Sep	All reaches
F8	High-flow pulse	Maintenance of appropriate† salinity gradient in estuary	≥ 1 per year / duration to be determined*	≥ 4 in 5 years	Apr-May	Reach 4
F9	Low flow and high flow	Maintain area‡ of D ≥ 1.5 m[1,2] and V ≤ 1.0 m/s[1,2]	Continuous	≥ 75% of the time	All year	All reaches
F10	Low and high-flow pulses	Achieve sufficient depth* to replenish/maintain water in river associated wetlands and backwaters	≥ 2 per year / ≥ 1 day	≥ 4 in 5 years	Jun-Nov and Dec-May	Reach 1
F11	Low flow and high flows	Maintain adequate cross-sectional area/discharge* to transport nutrients required to sustain primary productivity	Continuous	≥ 75% of the time	All year	Reaches 3 and 4
F12	Bankfull	2,600 - 4,000 m^3/s – see Geomorphologic objective G1	≥ 1 per year / ≥ 1 day*	≥ 4 in 5 years	Jun–Sep	Reach 1
F13	Bankfull	2,600 - 4,000 m^3/s – see Geomorphologic objective G2	≥ 1 per year / ≥ 1 day*	≥ 4 in 5 years	Jun–Sep	All reaches
F14	High flow	See Vegetation objective V1	Continuous	≥ 75% of the time	Jul–Oct	Reach 1
F15	High flow and low flow	See Vegetation objective V7	Variable	≥ 75% of the time	All year	Reach 4
F16	Low flow	Maintain mean pool velocity ≥ 0.01 m/s	Continuous	≥ 75% of the time	Nov–Mar	All reaches
F17	High flow and low flow	Sufficient discharge* to maintain morphology in and around the estuary mouth	Continuous	≥ 75% of the time	All year	Reach 4
F18	Bankfull	2,600 - 4,000 m^3/s – see Geomorphologic objectives G3 and G4	≥ 1 per year / ≥ 1 day*	≥ 4 in 5 years	Jun–Sep	Reach 4

‡ 'maintain area' means provide a percentage of the pre-dam area or an arbitrary area to be decided by the Scientific Panel on the basis of hydraulic/hydrologic analysis; * Tentative – to be refined on the basis of hydraulic/hydrologic analysis; † Data not available to determine criterion at this stage; 1. Personal communication, staff at Wuhan CAS Hydrobiology; 2. Jiang et al. (2010).

Table A6. Macroinvertebrate-based objectives

No.	Objective	Flow component	Hydrologic/hydraulic criteria	Mean annual frequency/ duration	Inter-annual frequency	Timing	Reach
M1	Prevent habitat loss through drying of shallow areas and pool crossings	Cease to flow	Q ≥ YRCC warning standards of low flow emergency	Continuous	100% of the time	All year	All reaches
M2	Maintain reasonable area of shallow habitat at pool crossings	High flow and low flow	≥ 80% of wetted area at pre-Sanmenxia median baseflow for each month	Continuous	≥ 75% of the time	Each month	All reaches
M3	Maintain submerged aquatic vegetation e.g. Vallisneria, Potomageton and Myrriophylum spp.	See vegetation objectives					
M4	Maintain aquatic emergent vegetation e.g. Phragmites and seasonally submerged meadow vegetation	See vegetation objectives					
M5	Maintain minimum 2 mg/L dissolved oxygen, particularly in deeper pools	Low flow and high flow	0.01 m/s to maintain mixing in larger riverine pools*	Continuous	≥ 75% of the time	Each month	All reaches
M6	Maintain favourable salinity at estuary and mouth for rearing of Chinese shrimp	High flows	191 ≤ Q ≤ 1227 m_3/s	≥ 50% of the time in Jun-Aug	≥ 75% of the time	June-Aug	Reach 4
M7	Maintain unconsolidated soft-bottom, substrates in estuarine backwaters and tributaries	Bankfull	Sediment load to maintain positive balance of sediment deposition over erosion in and around the estuary mouth. See geomorphology objectives.				Reach 4
M8	Maintain tidal flushing and associated salinity dynamics to support estuarine dependant species	Bankfull	Flow to scour estuary mouth and maintain adequate channel capacity for tidal flushing. See geomorphology objectives.				Reach 4

* Based on expert opinion; refinement of this criterion will require investigation.

Table A7. Vegetation flow objectives

No.	Objective	Flow component	Hydraulic/hydrologic criteria	Mean annual frequency/ duration	Inter-annual frequency	Timing	Reach
V1	Maintain submerged aquatic vegetation (e.g. *Vallisneria*, *Potomageton* and *Myriophyllum* spp.)	High flow	Inundation to ≤ 1 m	Continuous	≥ 75% of the time	Jul–Oct	Reach 1
V2	Maintain meadow vegetation	High flow	Inundation to ≤ 0.3 m	50 – 100% of time	≥ 75% of the time	Jun–Nov	Reach 1
V3	Maintain *Tamarix/Salix* shrubland	High flow, low flow and low flow pulse	100% of time shallow groundwater; Jul – Sep waterlogging; inundation by summer flow pulse events ≤ 30 days; soil salinity 10 – 30 psu	Variable	≥ 75% of the time	Jun–Feb	Reach 1
V4	Maintain *Tamarix/Salix* woodland	High flow, low flow and low flow pulse	100% of time shallow groundwater (at 1.5 – 3.0 m); inundation by summer flow pulse events ≤ 30 days; soil salinity 10 – 30 psu	Variable	≥ 75% of the time	All year	Reaches 1 and 4
V5	Maintain sand flats	High flow and low flow	100% of time shallow groundwater (at ≤ 1.8 m); soil salinity ≥ 30 psu	Continuous	≥ 75% of the time	All year	Reach 4
V6	Maintain *Suaeda salsa*	High flow pulse	Inundate once per year for ≤ 30 days or 30 to 180 days of varying depth from -0.1 to +0.1 m; 100% of time shallow groundwater (at 1.8 m); soil salinity 5 – 30 psu	Variable	≥ 75% of the time	Jun–Sep	Reach 4
V7	Maintain *Phragmites australis* grassland	High flow and low flow	100% of time waterlogging; varying inundation 0 – 0.5 m deep (1.5 m max.; 0.3 m mean) in summer	Variable	≥ 75% of the time	All year	Reach 4

Table A8. Low-risk environmental flow regime for Reach 1 of the lower Yellow River (Compliance point is Huayuankou)

Objectives met	Flow component	Hydrologic criteria	Mean annual frequency/ duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
B1; B2; B3, F2; WQ1, WQ2, WQ3, WQ4; V3; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 307 Jan ≥ 280 Feb ≥ 321 Mar ≥ 377 Apr ≥ 463 May ≥ 430	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9; V1; B5; M3; M4; F14	High flow	Jun ≥ 434 Jul ≥ 783 Aug ≥ 1,137 Sep ≥ 1,124 Oct ≥ 866 Nov ≥ 543	Continuous	≥ 75% of the time	Jun - Nov
V3; V4; F10	Low flow pulse	≥ 2000	≥ 1 per year / 1 – 30 days; rates of rise and fall within natural range	≥4 in 5 years	Nov - May
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3000 – 4000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep

Table A9. Medium-risk environmental flow regime for Reach 1 of the lower Yellow River (Compliance point is Huayuankou)

Objectives partly met	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
B1; B2; B3, F2; WQ1, WQ2, WQ3, WQ4; V3; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 185 Jan ≥ 174 Feb ≥ 191 Mar ≥ 229 Apr ≥ 284 May ≥ 263	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9; V1; B5; M3; M4; F14	High flow	Jun ≥ 265 Jul ≥ 466 Aug ≥ 754 Sep ≥ 744 Oct ≥ 534 Nov ≥ 335	Continuous	≥ 75% of the time	Jun - Nov
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3,000 – 4,000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep
V3; V4; F10	Not provided				

Table A10. Low-risk environmental flow regime for Reach 2 of the lower Yellow River (Compliance point is Sunkou)

Objectives met	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
F2; WQ1, WQ2, WQ3, WQ4; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 216 Jan ≥ 154 Feb ≥ 229 Mar ≥ 273 Apr ≥ 342 May ≥ 285	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9	High flow	Jun ≥ 266 Jul ≥ 362 Aug ≥ 584 Sep ≥ 580 Oct ≥ 532 Nov ≥ 362	Continuous	≥ 75% of the time	Jun - Nov
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3000 – 4000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep

Table A11. Medium-risk environmental flow regime for Reach 2 of the lower Yellow River (Compliance point is Sunkou)

Objectives partly met	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
F2; WQ1, WQ2, WQ3, WQ4; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 108 Jan ≥ 86 Feb ≥ 115 Mar ≥ 130 Apr ≥ 159 May ≥ 133	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9	High flow	Jun ≥ 128 Jul ≥ 165 Aug ≥ 310 Sep ≥ 309 Oct ≥ 276 Nov ≥ 165	Continuous	≥ 75% of the time	Jun - Nov
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3000 – 4000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep

Table A12. Low-risk environmental flow regime for Reach 3 of the lower Yellow River (Compliance point is Luokou)

Objectives met	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
F2; WQ1, WQ2, WQ3, WQ4; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 343 Jan ≥ 219 Feb ≥ 362 Mar ≥ 410 Apr ≥ 427 May ≥ 417	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9	High flow	Jun ≥ 394 Jul ≥ 509 Aug ≥ 603 Sep ≥ 601 Oct ≥ 543 Nov ≥ 445	Continuous	≥ 75% of the time	Jun - Nov
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3000 – 4000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep

Table A13. Medium-risk environmental flow regime for Reach 3 of the lower Yellow River (Compliance point is Luokou)

Objectives partly met	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
F2; WQ1, WQ2, WQ3, WQ4; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 225 Jan ≥ 143 Feb ≥ 234 Mar ≥ 260 Apr ≥ 277 May ≥ 264	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9	High flow	Jun ≥ 248 Jul ≥ 324 Aug ≥ 355 Sep ≥ 355 Oct ≥ 337 Nov ≥ 283	Continuous	≥ 75% of the time	Jun - Nov
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3000 – 4000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep

Table A14. Low-risk environmental flow regime for Reach 4 of the lower Yellow River (Compliance point is Lijin)

Objectives met	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
WQ1, WQ2, WQ3, WQ4; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 303 Jan ≥ 189 Feb ≥ 314 Mar ≥ 332 Apr ≥ 379 May ≥ 342	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9, M6, F8	High flow	Jun ≥ 332 Jul ≥ 436 Aug ≥ 447 Sep ≥ 446 Oct ≥ 441 Nov ≥ 412	Continuous	≥ 75% of the time	Jun - Nov
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3000 – 4000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep

Table A15. Medium-risk environmental flow regime for Reach 4 of the lower Yellow River (Compliance point is Lijin)

Objectives partly met	Flow component	Hydrologic criteria	Mean annual frequency/duration	Inter-annual frequency	Timing
F1; M1	Cease to flow	No cease to flow	Continuous	100% of the time	All year
WQ1, WQ2, WQ3, WQ4; M2; M5; F3; F4; F11; F16	Low flow	Dec ≥ 212 Jan ≥ 116 Feb ≥ 217 Mar ≥ 224 Apr ≥ 239 May ≥ 227	Continuous	≥ 75% of the time	Dec - May
F6; F7; F9, M6, F8	High flow	Jun ≥ 224 Jul ≥ 278 Aug ≥ 284 Sep ≥ 283 Oct ≥ 281 Nov ≥ 263	Continuous	≥ 75% of the time	Jun - Nov
G1, G2, G3, G4, WQ6; B6; B7; B8; F12; F13; F5; F10	Bankfull	3,000 – 4,000	≥ 1 per year / ~10 – 30 days duration; rates of rise and fall within natural range	≥4 in 5 years	Jun – Sep