

# Modelling the impacts of reservoir operations on the downstream riparian vegetation and fish habitats in the Lijiang River

Ruonan Li, Qiuwen Chen and Fei Ye

## ABSTRACT

River flow regulations have great impact on the downstream aquatic ecosystem. It is important to investigate the response of target species to the changes in hydrological regimes so that we can explore possible remediation measures. Ecohydraulics models that integrate hydrodynamics processes and ecological processes have been shown to be efficient in achieving these objectives. This study developed an integrated model which combined a two-dimensional hydrodynamic module with a vegetation evolution module and a fish habitat module. Owing to the ability to represent spatial heterogeneity and local interactions, the vegetation module used an unstructured cellular automata (UCA) approach. To describe the ambiguous relations between the physical conditions and habitat suitability, a fuzzy inference method was applied to the fish habitat module. The developed model was applied to a compound channel of the Lijiang River in southwest China, which has been greatly affected by the flow regulations of the Qingshitan Reservoir for navigation purposes. Through scenario simulations, the effects of flow regulation on riparian vegetation and fish habitat were analyzed. According to the results, water releases in the dry season imposed negative effects on the downstream semi-aquatic plant *Rumex maritimus* (*R. maritimus*) and *Polygonum hydropiper* (*P. hydropiper*) and favored the upland species *Leonurus heterophyllus* (*L. heterophyllus*). Regarding to the effects on fish *Spinibarbus hollandi* (*S. hollandi*) the results showed that water releases increased the suitability of the spawning conditions, especially during wet and dry years, but had little impact on the overwintering conditions.

**Key words** | cellular automata, fuzzy inference, habitat modelling, river ecosystem, river regulation

Ruonan Li

Qiuwen Chen (corresponding author)

Fei Ye

Research Centre for Eco-Environmental Sciences,  
Chinese Academy of Sciences,  
Shuangqing Road 18,  
Haidian District,  
Beijing, 100085,  
China  
Tel.: +86 10 6284 9326  
Fax: +86 10 6284 9326  
E-mail: qchen@rcees.ac.cn

## ABBREVIATION AND NOTATION

ADI	alternating direction iterations
CA	cellular automata
FI	fuzzy inference
MD	membership degree
NR	no reservoir operation
WR	with reservoir operation
QST	Qingshitan Reservoir
UCA	unstructured cellular automata
$Qa$	discharge or withdrawal, $m^3/s$
$H$	water level, m

$u$	velocity in $x$ direction, m/s
$v$	velocity in $y$ direction, m/s
$\nu$	horizontal eddy viscosity coefficient, $m^2/s$
$f$	Coriolis parameter
$\tau_x$	bottom shear stress in $x$ direction, N/m
$\tau_y$	bottom shear stress in $y$ direction, N/m
$c$	concentration, $kg/m^3$
$D_x$	disperse coefficient in $x$ direction, $m^2/s$
$D_y$	disperse coefficient in $y$ direction, $m^2/s$
$S$	source or sink term
$f_R(c, t)$	reaction term

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$\phi$	heat flux into water body, $\text{W}/\text{m}^2$
$\rho$	water density, $\text{g}/\text{m}^3$
$C_p$	specific heat of water, $\text{J}/\text{kg}^{-1}$
$h$	water depth, m
$\phi_s$	net solar radiation, $\text{W}/\text{m}^2$
$\phi_{so}$	total solar radiation in sunny day, $\text{W}/\text{m}^2$
$\gamma$	surface reflectance ratio, 0.03
$C$	cloud coverage rate
$W$	wind speed at 10 m above surface, m/s
$f(W)$	wind function, $\text{W}/\text{m}^2 \text{ mmHg}$
$T_s$	water surface temperature, K
$T_d$	dew point temperature, K
$\phi_c$	heat conduction flux, $\text{W}/\text{m}^2$
$T_a$	air temperature at 2 m above surface, K
$\bar{R}$	mean annual runoff, $10^8 \times \text{m}^3$
$C_v$	variation coefficient
$C_s$	skewness coefficient
$R_k$	available resource in cell $k$
$B_i^k$	biomass of species $i$ in cell $k$
$B_i^{neib}$	biomass of intruders (species $i$ ) from neighboring cells (in a triangular mesh, one cell has three neighbors)
$S_s$	area of the sample site, $\text{m}^2$
$n_i$	number of plant $i$ which grows under optimal conditions
$M_{i_{max}}^i$	maximum biomass of an individual plant under optimal conditions
$WUA$	weighted usable area, $\text{m}^2$
$HHS$	hydraulic habitat suitability index
$A_i$	horizontal surface of cell $i$ , $\text{m}^2$
$HSI_i$	habitat suitability index of cell $i$

## INTRODUCTION

The river ecosystem is known to have a close relationship with the hydrological regime (Costanza *et al.* 1997; Whiting 2002; Hironobu *et al.* 2003; Tomlinson & d'Carlo 2003). In recent decades, water resources exploitation and hydropower development have severely altered the natural flow conditions and thus damaged the structure and function of river ecosystems. Usually, large reservoirs possess greater operational capacity, and hence are associated with more serious impacts on the habitat of fauna and flora in downstream river reaches.

Habitat is the geographic location that provides creatures with suitable living space, food and reproductive environment. Each habitat is characterized by a number of interrelated environmental factors. These biotic and abiotic factors form the ecological niche, a multidimensional space (Hutchinson 1978; Wetzel 2001; Jochen *et al.* 2008). All the parameters (e.g. temperature, pH, flow velocity, availability of resources) can be attributed to a species-specific range, in which these factors can be tolerated, and to an optimum where organisms are usually most abundant (Jochen *et al.* 2008). Changes in these factors can have great impact on the growth, reproduction and distribution of species, where negative effects are associated with habitat degeneration (Moutona *et al.* 2007).

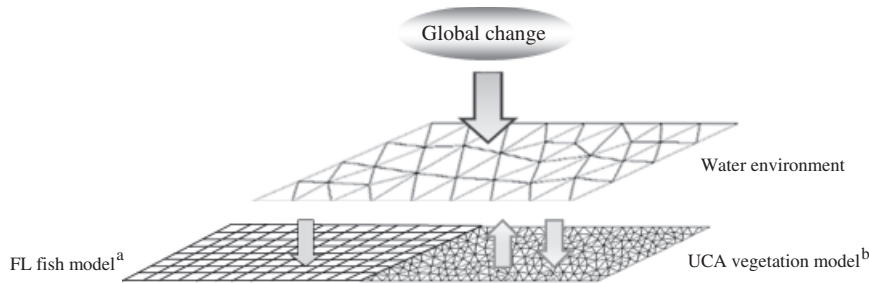
Following the rapid increase in the public awareness of ecological impacts associated with changes in river flow regimes, there are strong demands to quantitatively investigate other than qualitatively assess the impacts of reservoir operations and seek for implementable remediation measures (Nagaya *et al.* 2008; Schiermeier *et al.* 2008). To achieve such objectives, *in situ* monitoring and numerical simulation are usually adopted to track the changes in the aquatic species populations and distributions. Because of the high cost and the long period of empirically based monitoring programs, numerical simulation based on physical mechanisms has become the major method.

An ecohydraulics model, which integrates hydrodynamic and ecological processes, has been shown to be a useful tool to evaluate altered flow regimes and consequently the reshaping of habitat structures (Dynesius & Nilsson 1994; Chen & Ouyang 2005; Naiman *et al.* 2005; Nilsson *et al.* 2005).

This research took a compound channel of the Lijiang River as the study case and developed an integrated ecohydraulics model. The model was applied to investigate the impacts of the upstream Qingshitan Reservoir operations on the downstream fish habitat and riparian vegetation so as to provide suggestions on how to optimize the flow regulations for ecological concerns.

## METHOD

To deal with the interrelated abiotic and biotic processes in river ecosystem, a habitat model (Figure 1) was developed



**Figure 1** | The framework of the integrated model. (a) FI fish model integrated with hydrodynamic and water quality module. (b) UCA vegetation module integrated with hydrodynamic module.

that integrated a water environment module based on partial differential equations, a vegetation dynamic module based on unstructured cellular automata and a fish habitat module based on a fuzzy inference method.

### Water environment module

The hydrodynamics of the study reach was modelled by the two-dimensional shallow water equations (1)–(3) and the water quality was modelled by the two-dimensional advection–diffusion equation (4) with source/sink and reaction terms (Huang & Li 2006).

$$\frac{\partial H}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = Q_a \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho_0} \frac{\partial p}{\partial x} + fv + v \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + \frac{1}{\rho_0 H} \tau_x \quad (2)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho_0} \frac{\partial p}{\partial y} - fu + v \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + \frac{1}{\rho_0 H} \tau_y \quad (3)$$

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} = D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} + S + f_R(c, t) \quad (4)$$

where  $Q_a$  is discharge or withdrawal,  $H$  is water level,  $u$ ,  $v$  are velocity in  $x$  and  $y$  directions,  $\nu$  is horizontal eddy viscosity coefficient,  $f$  is Coriolis parameter,  $\tau_x$ ,  $\tau_y$  are bottom shear stress,  $c$  is concentration,  $D_x$ ,  $D_y$  are dispersion coefficients,  $S$  is source or sink term and  $f_R(c, t)$  is reaction term. For water temperature simulation,  $c$  is substituted by  $T$ , and  $f_R(c, t)$  is rewritten as  $dT/dt = \phi/(\rho C_p h)$ .

An implicit scheme was applied to solve the equations numerically. To reduce the band of the coefficient matrix in the implicit scheme, an alternating direction iteration (ADI) method was implemented (Lu & Guan 2004).

It had been well known that reservoir operation largely changed water temperature and dissolved oxygen concentrations that have a large impact on the river ecosystem. According to the field study, the variations of dissolved oxygen concentrations in the study area were not significant. Therefore, only water temperature was taken into account in the water quality module. Water temperature is related to solar radiation and heat exchange between air, the water body and river bed. However, heat exchange between river bed and water body were usually negligible (Su & Tu 2003). Thus, the reaction term  $f_R(c, t)$  in Equation (4) was changed into the following:

$$f_R(c, t) = \frac{dT}{dt} = \frac{\phi}{\rho C_p h} \quad (5)$$

$$\phi = \phi_s - \phi_e - \phi_c \quad (6)$$

$$\phi_s = \phi_{so}(1 - \gamma)(1 - 0.65C^2) \quad (7)$$

$$\phi_e = \beta f(W)(T_s - T_d) \quad (8)$$

$$\phi_c = 0.47f(W)(T_s - T_a) \quad (9)$$

where  $\phi$  is heat flux into water body,  $\rho$  is water density,  $C_p$  is specific heat of water,  $h$  is water depth,  $\phi_s$  is net solar radiation,  $\phi_{so}$  is total solar radiation in sunny day,  $\gamma$  is surface reflectance ratio 0.03,  $C$  is cloud coverage rate,  $f(W)$  is wind function,  $f(W) = 9.2 + 0.46W^2$ ,  $W$  is wind speed at 10 m above surface,  $T_s$  is water surface temperature,  $T_d$  is dew point temperature,  $\beta = 0.35 - 0.015T + 0.0012T^2$ ,  $T = (T_s + T_d)/2$ ,  $\phi_c$  is heat conduction flux and  $T_a$  is air temperature at 2 m above surface.

## Riparian vegetation module

For decades, the ecological value of riparian vegetation has been appreciated. Different kinds of models have been developed to assess and predict the impact of river regulations on riparian plants. Of these approaches, statistical models were first and also widely used (Franz & Bazzaz 1977; Hill & Keddy 1992; Toner & Keddy 1997; Hill *et al.* 1998). However, the weakness of the statistical method lies in its static feature. To get a better understanding of riparian system dynamics and its underlying processes, a process-based method is needed.

Process-based models present a more continuous view of riparian dynamics based on historical plant establishment requirements and channel evolution features. But these models were mostly aggregated, which failed to reflect the spatial heterogeneity and local interactions (Hupp & Osterkamp 1996; Perry & Enright 2007). As an alternative, spatially explicit approaches such as cellular automata were explored (Chen *et al.* 2002; Perry & Enright 2007; Chen & Ye 2008).

The spatially explicit approach of cellular automata was applied in the research to develop a riparian vegetation module. Cellular automata is a mathematical system in which the simple local components interact together to produce complicated global dynamics (Alonso & Sole 2000; Chen *et al.* 2002).

In the vegetation model, the study area was discretized into a triangular mesh. When properly configured, a smooth transition between cells of different sizes could be achieved, which facilitated local refinements in the computational mesh (Shewchuk 2002). In such a manner, cell size was adjusted according to the scale of local processes, so as to obtain a better representation of the real system.

A set of evolution rules had to be defined reflecting the lifecycle of species and describing how modelled plants respond to external disturbances and how they compete with each other. These rules were drawn from field investigations, controlled experiments and expert empirical knowledge. The rules vary with specific cases, and for this study the detailed rules are given in the next section.

## Fish habitat module

Since the 1980s, fish habitat analysis has already been an important part of river health assessment. There was

plenty of research that assessed fish living environment from various aspects such as hydraulic, water quality, physiological functions and processes (Hawkins 1975; Fremling *et al.* 1989; Barmuta 1989, 1990; Scruton *et al.* 1998; Blachuta & Witkowski 1990; Kemp *et al.* 1999; Crkspin & Usseglio 2002; Detenbeck *et al.* 2003; Vilizzi *et al.* 2004). So far, fuzzy logic, artificial neural network (ANN), regression analysis and decision trees have been widely used in fish habitat assessment (Binns & Eiserman 1979; Copp 1992; Hayes & Jowett 1994; Baptist *et al.* 1997; Jorde *et al.* 2001; Willhelm *et al.* 2005; Zuther *et al.* 2005; Dakou *et al.* 2007).

Limited by the availability of ecological data and the knowledge of the underlying mechanism, development of pure data-driven or process-based ecological models was restricted. Fuzzy logic has shown a great ability to deal with imprecise data and the ambiguous relation between abiotic/biotic relations. In addition, it can easily incorporate the empirical knowledge of domain experts (Chen & Mynett 2004). Thus, the fuzzy inference method is very suitable for ecological modeling, including habitat assessment. Therefore, it was applied in this study to develop a module for evaluating and predicting fish habitat changes represented by the habitat suitability index.

In the fuzzy inference model, the membership functions and inferring rules usually come from domain expert knowledge. Nowadays, there is plenty of research about extracting rules and membership functions from data by machine learning techniques, e.g. case reasoning (Chen & Mynett 2003) and feature reasoning (Chen & Mynett 2004). In this study, both domain expert knowledge and field monitored data were used to define the membership functions and fuzzy inferring rules. The input parameters were selected according to their importance to the specific species and their values were provided by the outputs of the water environment module.

The fuzzy inferring rules were implemented through a set of if and then clauses. The geometric mean approach was used in the module for inference combination and the center of gravity was applied for defuzzification, which transforms the fuzzy outputs into crisp values. Similar to the vegetation module, the rules vary with specific cases. In this study, the inference rules of habitat changes are given in the next section.

## Model integration

For the spatial integration, the discrete nature of the modules facilitates the data exchange between them. Although the mesh configuration was different, the same coordinate system was shared. To guarantee numerical stability, the time step of the water quality module was chosen according to Courant number restriction. It was 60 s in this study for both numerical convergence and computation efficiency. However, it is not necessary to make an assessment of habitat changes every 60 s, and usually daily variations were analyzed. Thus, there was a time scaling between the water environment module and the ecological (vegetation and fish habitat) modules. At each time step of the ecological modules, the riparian vegetation and fish habitat modules read the daily averaged outputs from the water environment module and carried out their respective computations.

## CASE STUDY

The developed model was applied to the compound channel near the Yangshuo station of the Lijiang River, which is located in the southwest of China (Figure 2). Due to the special karst landscape and the strong seasonality of rainfall, the discharges at the Yangshuo station vary from 12 m<sup>3</sup>/s to 12 000 m<sup>3</sup>/s, with an annual average of 120 m<sup>3</sup>/s. The recorded minimum discharge was 8 m<sup>3</sup>/s, which imposed great threats to the local water supply and aquatic ecosystem. More importantly, river-based tourism is the predominant

income of the local economy. When the discharge is lower than 30 m<sup>3</sup>/s at the Guilin hydrologic station, the river cruiser cannot navigate to the world-famous Yangshuo Resort. During the dry period from October to the following March, there is a serious problem associated with river navigation, thus affecting the local economy. Therefore, a series of reservoirs have been or will be constructed in the main stream and its tributaries upstream of Lijiang River. At the moment, only the Qingshitan Reservoir is in operation.

When all the reservoirs are in operation, the minimum flow during the dry season is expected to reach 60 m<sup>3</sup>/s. Since the flow regimes have been dramatically altered by the Qingshitan Reservoir and will be further modified, it is important to quantitatively evaluate the influences of the proposed altered flow regimes on the downstream aquatic ecosystem and evaluate possible optimization schemes to reduce or remediate potential impacts. Such studies include simulation and calibration of water environment changes (Li *et al.* 2009), fish population dynamics (Li *et al.* 2010) and riparian vegetation successions (Chen & Ye 2008).

## Data collection

The hydrological and meteorological data during 1958–2004 were collected from the Yangshuo hydrological and meteorological station, including cross-section geometry, daily averaged discharge, water level, water quality parameters, irradiance and wind. In addition, the historical survey records of the aquatic vegetation and fish were collected as well from Guangxi Institute of Fisheries and Guangxi Department of

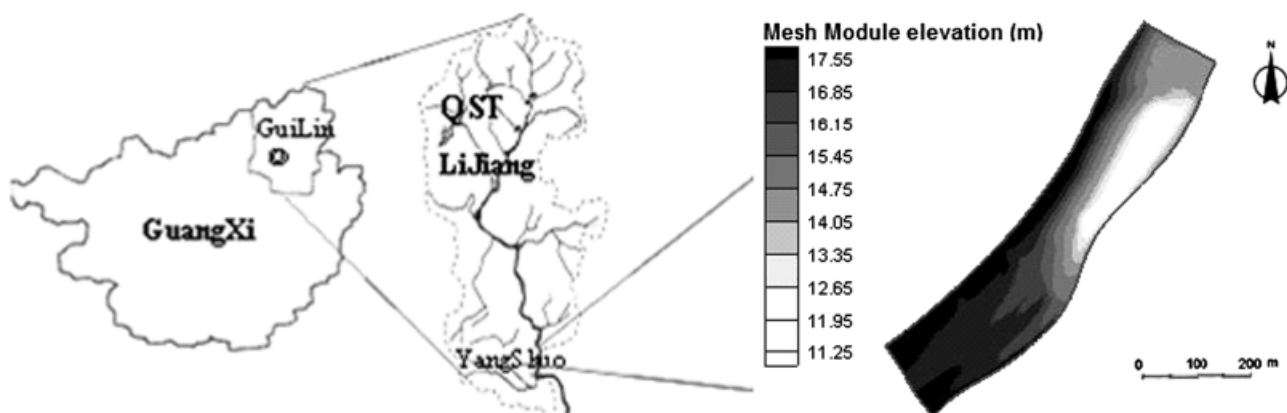


Figure 2 | The case study area (reference elevation: 86.4 m).

**Table 1** | Typical hydrologic years

	Wet year ( $p = 10\%$ )	Even year ( $p = 50\%$ )	Dry year ( $p = 90\%$ )	$\bar{R}$	$C_V$	$C_S/C_V$
Year	1993	1999	2004	40.59	0.21	2.0

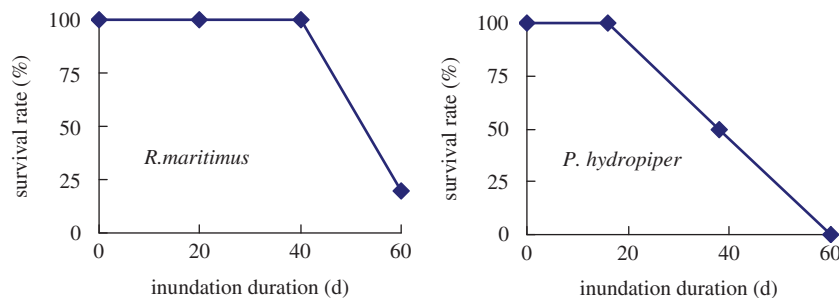
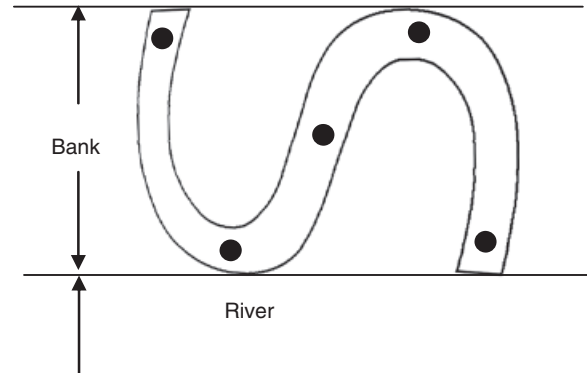
Water Resource (He 2007; Zhou 2007; Zhou & Han 2007; Zhou & Lei 2007).

Since the reservoir started to release water in the dry season from 1987 and the focus was to investigate the impact of reservoir regulations, three typical hydrological years after 1987 were selected for study (Table 1).

The bathymetry and the flow profiles of the studied river section were measured by a Doppler flow measurement device, River-Cat, which is manufactured by SonTek/YSI. In total, 15 cross sections were measured and the data for the entire area were obtained by interpolation. The interval between each two cross sections was within 50–70 m. The water quality data including water temperature, dissolved oxygen, pH and salinity were measured monthly by the multi-parameter water quality meter YSI6800. The chemical parameters were analyzed in the laboratory.

### Initial and boundary conditions

Daily averaged discharge was applied at the upstream boundary and daily averaged water level was applied at the downstream boundary. Monthly data were used for the boundary conditions for the water quality simulations. The time step was 15 min and the output data were the daily averaged value at each grid location.

**Figure 4** | Response curve of *R. maritimus* and *P. hydropiper* to inundation stress.**Figure 3** | Distribution of samples. •: Sample point.

### Vegetation species and evolution rules

Ten sites were surveyed on each bank along the river section within the study site. At each site, five points that formed an 'S' shape (Figure 3) were sampled and each point had a size of 1 m × 1 m. Three herbs were identified as the dominant species in the study area, including two typical wetland species *Rumex maritimus* and *Polygonum hydropiper*, and one upland species *Leonurus heterophyllus*. The number and the dry weight of these three typical species were counted at each point.

The physiological parameters of each species were obtained from control experiments (Figure 4) by using flume and green house, and the existing literature (Timson 1965, 1966; Mitchell 1976; Carter & Grace 1990; Vandersman et al. 1993a, b; Nabben et al. 1999). Both of the two hygrophyte species, *R. maritimus* and *P. hydropiper*, showed flood tolerance. *R. maritimus* is able to survive 40 days of inundation, while the tolerance period is shorter for *P. hydropiper*.



**Table 2** | Empirical values for the parameters of the vegetation module

Items	<i>R. maritimus</i>	<i>P. hydropiper</i>	<i>L. heterophyllus</i>
Seed weight	0.0002 g	0.002 g	0.0002 g
Max. growth rate*	0.13	0.12	0.13
Max. biomass per plant	2.70 g	1.65 g	3.00 g
Biomass loss rate during inundation	0 <sup>†</sup>	0.02/d	/ <sup>‡</sup>
Mortality rate during inundation	0.05/d (I.D. > 40 d) <sup>§</sup>	0.025/d (I.D. > 10 d)	0.8/d (I.D. > 5 d)
Growth rate decrease during drought	63% (D.D. > 5 d) <sup>  </sup>	27% (D.D. > 15 d)	0
Mortality rate during drought	0.05/d (D.D. > 10 d)	0.05/d (D.D. > 20 d)	0

\*The definition of growth rate is  $dw/dt$ , where  $w$  is the weight when it begins to grow and  $t$  is the time. The unit is g/d.

<sup>†</sup>"0" indicates no biomass loss but not normal growth.

<sup>‡</sup>*L. heterophyllus* suffers great biomass loss during inundation, with an assumed mortality rate of 0.1–0.2/d during short period of inundation.

<sup>§</sup>I.D. : inundation duration.

<sup>||</sup>D.D. : drought duration.

Table 2 lists some important parameters used in the vegetation module.

The following rules are specified for the cellular automata module.

- (1) Germination: in the riparian zone, seeds germinate along with the recession of the first flood after winter dormancy. Due to the relatively high dispersal ability and long dormancy of herbaceous seeds, the compositions of herbaceous seed banks are assumed abundant and evenly distributed. Therefore, the seed availability was not considered as a limiting factor for the herbaceous species. During the initialization of the model, seeds of the three species are scattered evenly in simulation space.
- (2) Growing period: the juvenile plants are most prone to adverse environmental disturbances (Vartapetian & Jackson 1997). The susceptibility (or tolerance) differs among the species (Table 1), which contributes to the vertical gradients of vegetation distribution. *R. maritimus* and *P. hydropiper* are typical hygrophite species, while *L. heterophyllus* is not adapted to inundation and mostly occurs on higher land where floods seldom reach.
- (3) Mature period: mature plants of the three species show much more tolerance to adverse environmental locations. They all are able to survive longer inundation or drought stress, and the survival rates are similar. The seeds are produced in this period.
- (4) Winter loss: all the annual herbaceous plants die in the winter and the seeds have an assumed loss rate.

- (5) The species competition rule is formulated according to field survey and lab experiments. The basic idea is: the resource of a given area is limited; if the plants growing on it exceed its capacity then competition takes place. Suppose the resources per unit area is  $R=1$  (resources/m<sup>2</sup>) and the resource consumption of species  $i$  is

$$C_i = S_s / (n_i \times M_{max}^i) \quad (10)$$

where  $S_s$  is the area of the sample site,  $n_i$  is the numbers of plant  $i$  which grow under optimal conditions and  $M_{max}^i$  is the maximum biomass of an individual plant under optimal conditions. Taking *R. maritimus* as an example, the field survey found that, in the most suitable environment, the maximum number of *R. maritimus* is 3 and the maximum biomass of a single plant is 2.7 g, so the corresponding consumption of *R. maritimus* is  $C_i = 1 / (3 \times 2.7)$ . Thus, the available resource in cell  $k$  is defined as

$$R_k = 1 - \sum_{i=1}^n (C_i \times B_i^k) - \sum_{neib=1}^3 \sum_{i=1}^n (C_i \times B_i^{neib}) \quad (11)$$

where  $R_k$  is the available resource in cell  $k$ ,  $B_i^k$  is the biomass of species  $i$  in cell  $k$  and  $B_i^{neib}$  is the biomass of intruders (species  $i$ ) from neighboring cells (in a triangular mesh, one cell has three neighbors). The details of the competition rules are illustrated in Table 3.

**Table 3** | CA rules describing species competition

	Resources available in local cell	No resources in local cell		No resources in local cell or neighborhood
		Co-exist with other species	Single species in cell	
<i>L. heterophyllus</i>	Normal growth	Keep growing at the cost of other species*	Search neighboring resources	Stop growing
<i>P. hydropiper</i> & <i>R. maritimus</i>	Normal growth	Search for neighboring resources*	Search for neighboring resources	Stop growing

\*As a stronger competitor, *L. heterophyllus* is able to keep normal growth when co-exists with other species and eventually out-compete weak competitors such as *R. maritimus* and *P. hydropiper*.

### Fish species and fuzzy rules

The main commercial fish in the Lijiang River, *Spinibarbus hollandi*, was selected as the study species. *S. hollandi* prefers living in a river with rushing current, clear water and gravel bed and is distributed in the upper and middle branches of the Zhujiang river basin.

The commercial yield of *S. hollandi* was second only to carp before the 1970s in the Lijiang River, but it decreased sharply in recent years due to over-fishing. Hu et al. (2003) determined the critical temperature and dissolved oxygen of *S. hollandi*. According to Hu et al. (2003), water depth, velocity, water temperature and dissolved oxygen are the most important factors in the habitat selection of *S. hollandi*. It was found from the field observations that the dissolved oxygen in the studied sections did not have significant variation; therefore, it was excluded from our model inputs. Based on the collected data and the domain knowledge (Hu et al. 2003), the memberships of the input and output variables are given in Figure 5.

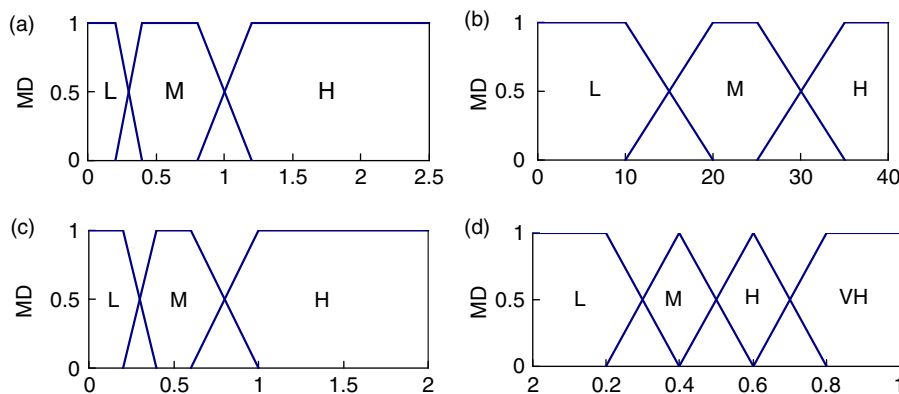
The fuzzy inferring rules were defined according to domain experts' knowledge, which is given in Table 4.

*S. hollandi* is a kind of freshwater and omnivorous fish, which spends its entire life including spawning, hatching and growing in rivers. The habitat use by different life stages is affected by many aspects. For the specific case in this study, three important factors including velocity, water depth and water temperature were selected based on empirical knowledge and data analyses.

According to the life cycle, the spawning period is mostly in the first half of the year, especially in late May and early June. The wintering period is often between December and January.

Following the work of Moutona et al. (2007), the weighted usable area (WUA) and the hydraulic habitat suitability index (HHS) were selected as the indexes in the model. The equations were given as

$$WUA = \sum_{i=1}^n A_i HSI_i \quad (12)$$



**Figure 5** | Membership degree. (a) Water depth, m, (b), water temperature, °C, (c) velocity, m/s, (d) Habitat Suitable Index (HSI). MD = Membership degree, L = Low, M = Medium, H = High and VH = Very high.



**Table 4** | Fuzzy rules used in the model

Water depth	Velocity	Water temperature	Habitat suitability	
			Spawning ground	Overwintering ground
L	L	L	L	L
L	L	M	L	M
L	L	H	L	L
L	M	L	M	L
L	M	M	H	M
L	M	H	M	M
L	H	L	L	L
L	H	M	M	M
L	H	H	L	M
M	L	L	M	L
M	L	M	H	H
M	L	H	M	M
M	M	L	H	M
M	M	M	VH	H
M	M	H	H	VH
M	H	L	M	M
M	H	M	H	H
M	H	H	M	H
H	L	L	L	L
H	L	M	M	M
H	L	H	L	M
H	M	L	M	M
H	M	M	H	H
H	M	H	M	H
H	H	L	L	M
H	H	M	M	M
H	H	H	L	M

L = Low, M = Medium, H = High and VH = Very high.

$$HHS = \frac{1}{\sum_{i=1}^n A_i} \sum_{i=1}^n A_i HSI_i \quad (13)$$

where  $A_i$  is the horizontal surface of cell  $i$  and  $HSI_i$  is the habitat suitability index of cell  $i$ .

The fuzzy inference module is given in Equation (14), which included four inputs and one output:

$$MD_{HSI} = \sqrt[4]{MD_D MD_T MD_V} \quad (14)$$

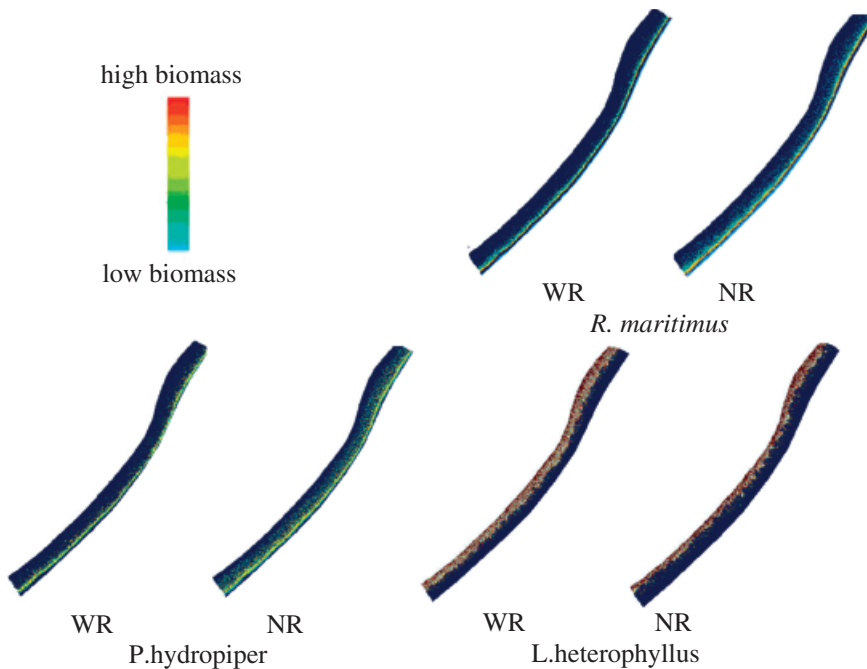
where  $MD_{HSI}$  is the membership degree of HSI,  $MD_D$  is the membership degree of water depth,  $MD_T$  is the membership degree of water temperature and  $MD_V$  is the membership degree of velocity. The inferring rules of HSI are presented in Table 4.

## RESULTS AND CONCLUSIONS

Figure 6 shows the comparison of two regulations in even flow years (1999 with and without reservoir operation). After reservoir operation, habitat availability was reduced for the semi-aquatic species (*R. maritimus* and *P. hydropiper*). Meanwhile, *L. heterophyllus*, which is more susceptible to flooding but more tolerant to drought, expanded towards the river side and colonized the habitat previously occupied by wetland species. This trend suggests that reservoir operations on the Lijiang River has an adverse effect on wetland species. In general, the modelled trend was consistent with field observations and the results obtained by statistical niche models, and the difference was mainly attributed to river regulation.

Figure 7 shows the mean biomass of each species in different elevation bands, i.e. the vertical gradient of the vegetation. Because the absolute weight of each species had a large variation, the relative biomass which was the proportion to the maximum plant biomass was used for illustration instead of the absolute biomass. The value ranged between 0 and 1, where 1 indicated the best growth. *R. maritimus* appeared close to the water line, and the mean biomass approached the peak at an elevation of a little higher than the base flow. As the elevation increases, *R. maritimus* disappeared gradually due to drought stress and competition from upland species. *P. hydropiper* followed a similar trend as *R. maritimus*, but the peak appeared at a higher elevation due to the difference in flood tolerance. *L. heterophyllus* flourished in the upland zone where floods seldom reached.

The modelled results in Figure 8 showed that *R. maritimus* and *P. hydropiper* flourished in the frequently disturbed areas, but barely survived under steady flow conditions. This is consistent with the previous findings that frequent fluctuations in water level may exclude upland species like *L. heterophyllus* and be more favorable to hygrophytes such as *R. maritimus* and *P. hydropiper* (Keddy & Reznicek 1982; Hill & Keddy 1992). The main reason lies in



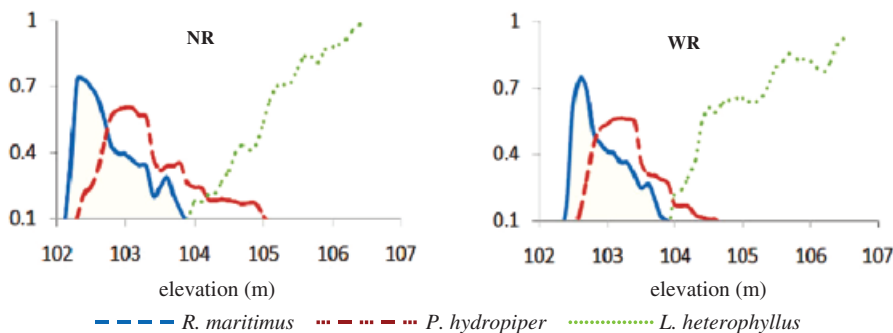
**Figure 6** | The distribution pattern of three species in even flow year under different conditions (riparian only). WR: with reservoir operation, NR: no reservoir operation.

the severe competition pressure and drought stress under steady state conditions.

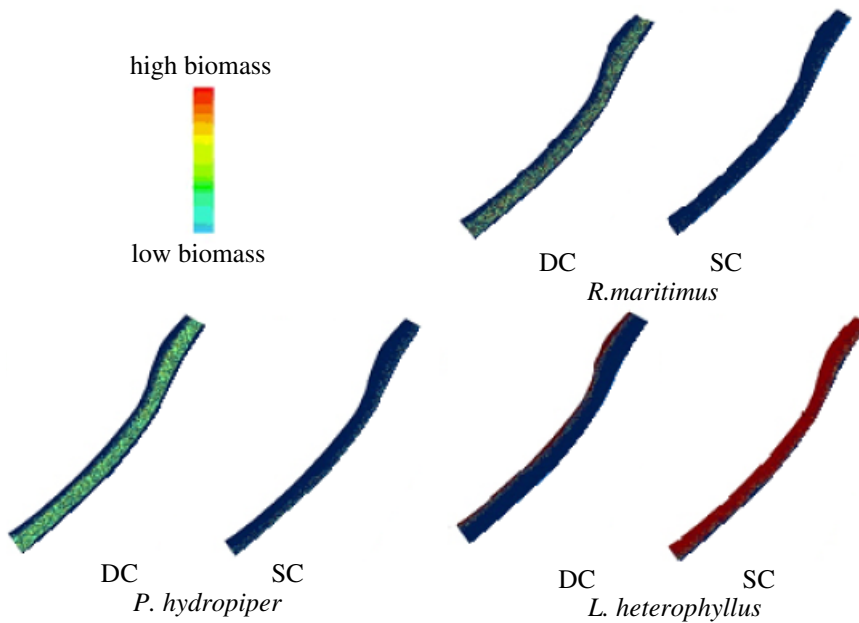
It has been recognized that not only the abiotic processes affected the plant distribution, but the interspecies competition played another important role (Grime 1973; Keddy 1985, 1989; Wilson & Keddy 1986; Day et al. 1988; Goldberg & Barton 1992). The potential habitat range of a certain species may greatly surpass what has been observed in the natural conditions. For example, Keddy (1989) proposed some hygrophyte species could also grow well in the shrub zone but are usually prevented by the stronger competitors from phreato-

phytes in that area. Figure 9 presents the modeled results of a scenario in which the more competitive upland species *L. heterophyllus* was artificially excluded. It was seen that, after the upland species was removed, the habitat range of *R. maritimus* and *P. hydropiper* spread landward, which was consistent with the existing theories and field experiments. The change in pattern was directly related to the relieved competition pressure from the upland species.

It was concluded from the modelled scenarios that the flow regulation of the Lijiang River had negative effects on the downstream riparian species *R. maritimus* and

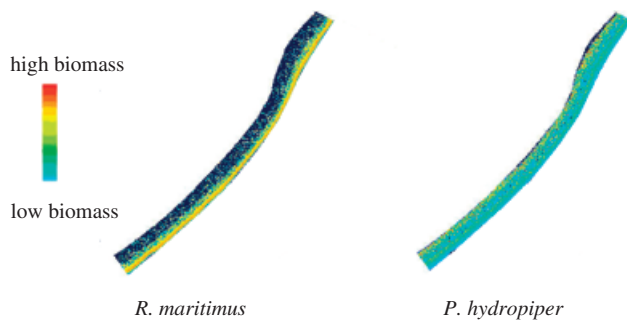


**Figure 7** | The biomass (relative value, proportion of maximum biomass of single plant) distribution with respect to elevation in even year under different conditions. WR: with reservoir operation, NR: no reservoir operation.



**Figure 8** | The distribution pattern of three species in two hypothesized flow regimes (riparian only). DC: frequently disturbed condition; SC: stable condition.

*P. hydropiper* that usually inhabit the dry-wet transition area. The modified flow regime seemed to favor the upland species *L. heterophyllus* to expand towards the river, thus gradually colonizing the space previously occupied by *R. maritimus* and *P. hydropiper*. Because the dry-wet transition areas usually have higher biodiversity than upland areas, the change induced by flow regulation would result in a loss of riparian vegetation diversity. Frequent fluctuations in water level could create favorable environments for hygrophytes and it can be artificially made through reservoir operations. Therefore, it should be adopted as a way to remediate impacts. However, more investigations on the entire river are still needed in order to give a comprehensive assessment.

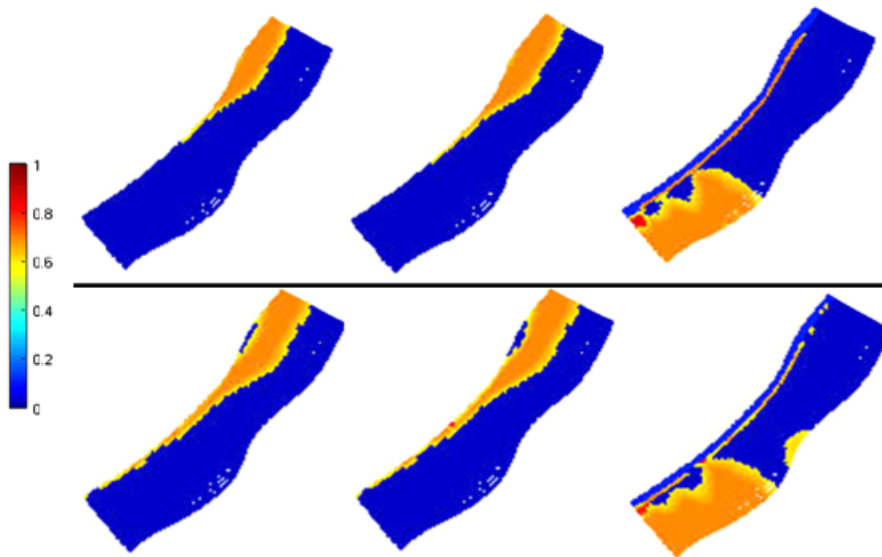


**Figure 9** | The distribution pattern of two hygrophyte species (riparian only) supposing the upland species (*L. heterophyllus*) is artificially excluded.

During the spawning period, reservoir operations caused the velocity and water level in the studied section to decrease by around 13% in a wet year and rise by 9% in a dry year. During the overwintering period, the averaged values of the two flow factors increased by about 1.5% in all three simulated years. For the water quality factors, reservoir operation resulted in water temperature to rise 0.1% on average. Habitat Suitability Index (HSI) values, however, changed significantly after the reservoir operations in the spawning period (Figure 10).

It is obvious that, after the reservoir operation, the area with high HSI values increases in all typical years. In wet and dry years, the area with high suitability ( $HSI > 0.5$ ) enlarged dramatically, nearly one and half times than before, but only slightly in even years. According to the results, the HSI reached a peak at the value of nearly 1 m/s in velocity and about 22°C in water temperature. The index decreased dramatically when the velocity is higher than 1.2 m<sup>3</sup>/s and water temperature is over 26°C. The most suitable areas are mainly located in places where water depth was lower than 3 m and is near the downstream area of the studied section in wet and dry years and near the upstream area in even years.

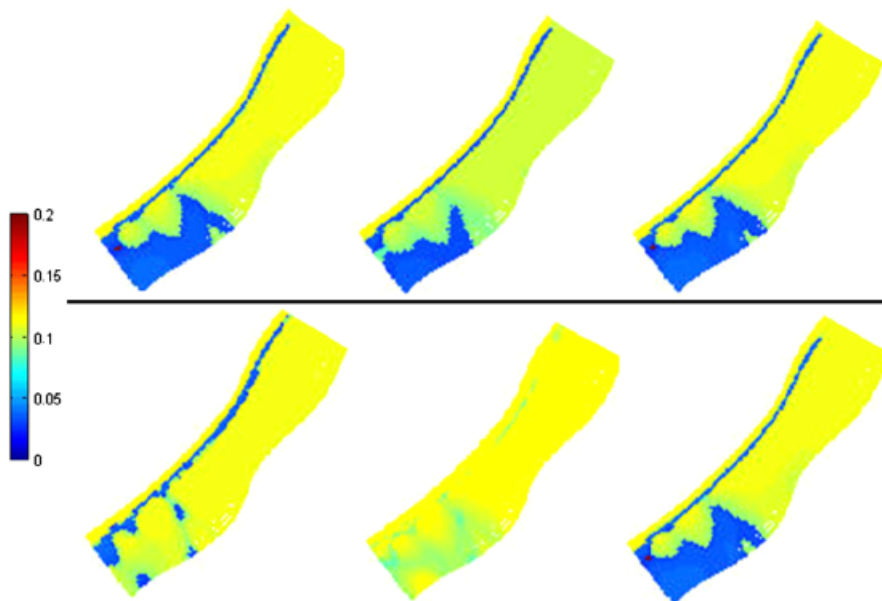
The HSI for overwintering are much lower than for spawning. Figure 11 shows that the values are all lower than 0.2 on average. Similar to the spawning results, the



**Figure 10** | *HSI* for spawning in typical years with and without reservoir operation (top: without reservoir operation; bottom: reservoir operation; left: wet year; middle: dry year; right: even year).

suitable area for overwintering increased with reservoir operation. The places with high *HSI* were around the deeper zone of the studied section. According to the model results, the *HSI* values were higher when the water temperature is about 11–13°C, the depth was over 1 m and the velocity was around 0.3–0.4 m/s.

Table 5 showed the changes in the *WUA* and *HHS*. The reservoir operation had great impact on the two indicators in wet and dry years, but had little effect in even years. The spawning area increased largely with the water releases in wet and dry years. The model results showed that the water releases contributed 44.2% to the increase of the high suitable



**Figure 11** | *HSI* for overwintering in typical years with and without reservoir operation (top: no reservoir operation; bottom: reservoir operation; left: wet year; middle: dry year; right: even year).

**Table 5** | *WUA* square meters and *HHS* with and without reservoir operation

		Spawning area (averaged from May 15 to June 15)		Overwintering area (averaged from December 15 to January 15)	
		Without	With	Without	With
<i>WUA</i>	Wet year	20982.2	32721.5	14821.2	15562.2
	Dry year	24549.7	32817.0	14591.4	16675.1
	Even year	27580.8	29438.8	14830.0	14838.6
<i>HHS</i>	Wet year	0.1398	0.2180	0.0987	0.1036
	Dry year	0.1635	0.2186	0.0972	0.1110
	Even year	0.1837	0.1961	0.0988	0.0989

( $HSI > 0.5$ ) spawning area, and it seemed that this channel was not suitable for fish overwintering.

The distribution of fish habitat is restricted mainly by short-term effects. For various life stages, fish are able to seek the area that fits best their physiological demands such as spawning and overwintering.

The model presented in the paper has taken four factors into account to evaluate the habitat suitability for the two life stages. Among these factors, velocity showed a significant correlation ( $r = 0.99$ ) and seemed to be the most important factor during the spawning period.

The substrate variations were not considered and the bed material was set to be gravel (10–15 cm). The previous researches showed that *S. hollandi* spawn on the gravel bed without aquatic plants. Field investigations indicated that the aquatic plants were flourishing in areas deeper than 2.5 m. Therefore, comparing to the real situation, the *HSI* were likely overestimated.

## DISCUSSIONS AND FUTURE WORK

The Qingshitan Reservoir operation led to the shrinking of semi-aquatic plants, but the expansion of upland species. Water releases dramatically increased the spawning area of *S. hollandi* in wet and dry years, whereas they had relatively small effect on the overwintering habitat area.

The cellular automata approach demonstrated the efficiency in modeling of riparian vegetation dynamics. Some essential processes in riparian plant communities had been

successfully captured, such as plant life cycle, plant response to environmental condition, and intra- and interspecies competition. Cellular automata also showed its compatibility with other numerical simulation techniques, such as finite-volume or finite-element models.

The major difficulty for most of the spatially explicit modeling is the requirement for detailed background information. A large amount of plant species are present in a river system, so it may not be practical or possible to capture the physiological characteristics of all the riparian species in a large spatial scale, except for dominant species and some rare endangered species. However, the difficulty may be alleviated by referring to some practical aspects of conventional statistical models. In statistical models, plant species are surveyed and grouped according to their niche preferences. Such “functional groups” (Hill *et al.* 1998; Blanch *et al.* 1999) can also be adopted in spatially explicit models. If the key species can be found to well represent its functional group, the effort in determining the plant characteristics can be considerably reduced and the spatially explicit modeling of a large scale may be realized.

The fuzzy rules of the fish habitat in this model were extracted mainly from the empirical knowledge of domain experts and a little field data. This may cause errors to some extent because the expert experience is mostly qualitative or semi-quantitative. More field data should be collected to extract fuzzy rules and optimize membership parameters simultaneously in forthcoming research by applying genetic algorithms.

The yield of *S. hollandi* decreases gradually over the years according to field investigations, whereas the area of habitat seems to increase with reservoir operation in three typical years. Expect for the obvious reason of overfishing, the impact of hydraulic engineering cannot be neglected. The *S. hollandi* often migrate between the main stream and the tributaries of the Lijiang River: however, the dam construction cut off the habitat connectivity. Therefore, the effect of habitat connectivity should be taken into account in the ongoing research.

The substrate variation is an important factor in simulating the feeding ground, which has not yet been included in the current model. It should be incorporated in further research after field investigations.

We understand that sensitive analysis is important to evaluate model performance with the change of parameters



and discover key variables. In this paper, the input variables were selected according to the physiology study results (Hu *et al.* 2003) of the target fish *S. hollandi*. The definition of the membership functions and the parameters values were based on the collected data and the domain knowledge. The parameters of the vegetation module came from the results of a series of controlled experiments in the laboratory by using flume and green house. The tested variables in the experiments included water depth, flow velocity and bed materials. Therefore, the model performance was deemed reliable. Future work involves collection of further data for better calibration of the parameters and analyses of model uncertainty as the existing field data are limited.

Although the field investigations have been done for three years (2006–2008), we are continuing the field investigations and monitoring twice a year (2009) to collect more data for model calibration so as to reduce parameter uncertainty. Meanwhile, we are improving the monitoring instruments to reduce data uncertainty.

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