Integrated Modelling Of Riparian Vegetation Dynamics Subjected To Reservoir Operation

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ABSTRACT

Since most of the world's large rivers are under regulation, it is imperative to quantify the impact of the flow modification on the associated riparian and aquatic ecosystem. Spatially-explicit ecological models provide a powerful tool to understand the dynamics of ecosystem. However, in this case, integration between ecological and hydrodynamic models is needed so as to effectively handle the interrelating physical and biological processes. This study developed an integrated model which combined spatially-explicit simulation of vegetation succession and numerical simulation of two-dimensional flow field to investigate the riparian vegetation dynamics under reservoir operations. The model was then applied to a compound channel of the Lijiang River in the Southwest China, which has been affected by the flow regulations for navigation purpose. Through the simulation, the previous evolutions of the riparian vegetation were recaptured and its future developments under further regulations were predicted. Finally, environmental friendly operation schemes were proposed based on the simulation results, and the pros and cons of this kind of models were discussed.

INTRODUCTION

Riparian zone is an interface between aquatic and terrestrial systems, which is characterized by its large environmental gradients and interrelating processes. The highly variable environment induced by flow fluctuation supports various plant communities, which in turn serve as nutrient buffer, bank stabilizer and habitats for native fauna . However, the state of riparian vegetation, especially for shrubs and herbs, is sensitive to disturbances and tends to be modified even by slight changes of hydrological regimes. While river regulations, such as dam construction, flow diversion and water withdrawal, have been a major agent in altering flow regimes and consequently reshaping the riparian structures (Dynesius and Nilsson 1994). Compared to natural changes, these anthropogenic disturbances are generally more drastic and often exert debilitating effects on plant communities. Thus, knowledge of how a riparian plant community response to human induced alterations is needed in order to preserve biodiversity and the functioning of riparian system.

For several decades, efforts have been made to understand the spatial patterns and evolution mechanisms of riparian plant communities. Different kinds of models have been developed to assess and predict the impact of river regulations on riparian plants. Among these approaches, conventional statistical models are widely used (e.g. Franz and Bazzaz 1977). The basic notion of this kind of models is to link the growing conditions of particular plant species with key variables that represent environmental factors. Without exploring deep into the underlying mechanism of riparian processes, the statistical manner greatly reduces the complexity of the problem. Statistical models serve as a convenient and practical way to predict vegetation patterns following flow alterations.

However, the weakness of statistical method lies in its static feature. In these models, the sampled and predicted vegetation patterns are assumed in "quasi-equilibrium". In the case of some highly dynamic systems, this equilibrium may be hard to find. Furthermore, these models only provide snapshots at each equilibrium, while the processes governing the riparian system are treated in a black box. Sometimes, the information about how the system evolves from one state to another is required. So, a process-based method is needed to get a better understanding of riparian system and its underlying processes.

Process-based models present a more continuous view of riparian dynamics based on historical plant establishment requirements and channel evolution features. The interaction between morphology change and vegetation succession are taken into account as well. But these models are mostly aggregated that fail to reflect

the spatial heterogeneity and local interactions (Hupp and Osterkamp 1996; Perry and Enright 2007). As an alternative, spatially-explicit approaches such as cellular automata are explored (Chen et al. 2002; Perry and Enright 2007). The conventional cellular automata models apply a structured grid, either square , or triangular or hexagon . However, ecosystems are mostly characterized by spatial anisotropy, which implies some important local features such as variations of turbulence intensity and microscopic topography must be well described.

In this study, a riparian vegetation module was developed using unstructured cellular automata based on irregular grid. Then it was integrated with a finite element hydrodynamic module to explicitly treat the interaction between stream flow and riparian plants. The model was applied to a compound channel of Lijiang River, where the flow was seriously regulated by the Qingshitan reservoir upstream. Historical annual vegetation survey records and the data collected during the research in 2006-2008 were used for model calibration and verification. Several scenarios either realistic or hypothesized were simulated to quantify the impacts of flow regulations on the riparian vegetation evolution. Meanwhile, the potential of this kind of models was largely explored. Finally, the pros and cons of spatially-explicit models were discussed.

METHODS

To deal with the interrelating physical and biotic processes in riparian system, an integrated framework which comprised a vegetation module and a hydrodynamic module was developed (Figure 1).
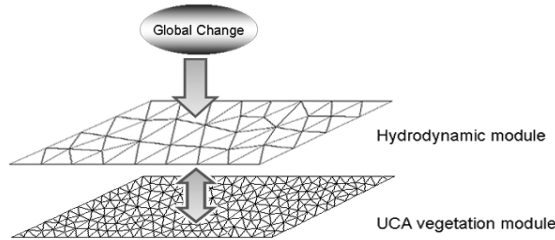

Figure 1. The model framework

Hydrodynamic module. The hydrodynamic module adopted a finite-element Eulerian-Lagrangian algorithm (Zhang and Baptista 2008; OHSU's Center for Coastal and Land-Margin Research) to solve the shallow water equations:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad \frac{\partial H}{\partial t}+\frac{\partial}{\partial x}\int_{H_{bottom}}^{H_{surface}}u\,dz+\frac{\partial}{\partial y}\int_{H_{bottom}}^{H_{surface}}v\,dz=0$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-g\frac{\partial H_{surface}}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(v\frac{\partial u}{\partial z}\right)+fv$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-g\frac{\partial H_{surface}}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(v\frac{\partial v}{\partial z}\right)-fu$$

where, $\mu(m^2\cdot s^{-1})$ and $v(m^2\cdot s^{-1})$ are the horizontal and vertical eddy viscosity coefficients respectively (typically $\mu \ll v$, and we consider $\mu = 0$ throughout the domain), $f(s^{-1})$ is the Coriolis factor. A hybrid S-Z coordinates was applied for vertical discretization, with terrain following S-layers used in shallow regions and staircase Z-layers in steep areas.

Riparian vegetation module. The spatially-explicit approach, cellular automata was applied in this research to develop a riparian vegetation module. Cellular automata is a mathematical system in which the simple local components interact with each other to produce complicated global dynamics (Chen et al. 2002; Packard and Wolfram 1985).

In the vegetation model, the study area was discretized into a triangular mesh. If properly configured, a smooth transition between cells of different sizes can be achieved, which facilitates local refinement (Shewchuk 2002). In such 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 to describe the lifecycles of species, how the modelled plants respond to external disturbances and how they compete with each other. These rules were drawn from field investigation, controlled experiments, and expert empirical knowledge.

Model integration. The discrete nature facilitates the data exchange between the two modules. Although the mesh configuration was different between the two modules, the same coordinate system was shared. In practice, the cellular automata mesh in the vegetation module was significantly finer than the finite element mesh in the hydrodynamic module, so the flow condition was assumed to be homogeneous within the area of a single vegetation cell. The values of hydrodynamic variables at each vegetation cell center were interpolated by the shape function from the finite element calibration. The simulation time step of the vegetation module was 1 day. At each step, the vegetation module read the outputs from the hydrodynamic module and calculated the influence on the local plants.

CASE STUDY IN LIJIANG RIVER

Study site. The developed model was applied to a compound channel near the Yangshuo station of the Lijiang River, which is located in the Southwest China (Figure 2). Due to the special Karst landscape and the strong seasonality of rainfall, the discharges at the Yangshuo station vary from $12m^3/s$ to $12000m^3/s$ with an annual average of $120m^3/s$. The recorded minimum discharge was $8m^3/s$, which imposed great threats to the local water supply and aquatic ecosystem. More importantly, the tourism is the predominant income of the local economy. When the discharge is lower than $30m^3/s$ at the Guilin hydrologic station, the cruiser cannot navigate to the world-famous Yangshuo resort. During the dry period from October to next March, there is a serious problem of cruise, thus affects the local economy. Therefore, a series of reservoirs have been or will be constructed in the main stream and tributaries in the upstream. At the moment, only the Qingshitan Reservoir is under operation.

When all the reservoirs are in operation, the low flow during dry season is expected to reach $60m^3/s$. Since the flow regimes have been drastically altered by the Qingshitan Reservoir and will be further modified, it is important to quantitatively evaluate the influences on the downstream aquatic ecosystem and explore possible optimization scheme to reduce or remediate the impacts. Such studies include flow condition changes (Li et al., 2008), fish population dynamics (Chen et al., 2008) and riparian vegetation successions presented in this paper.
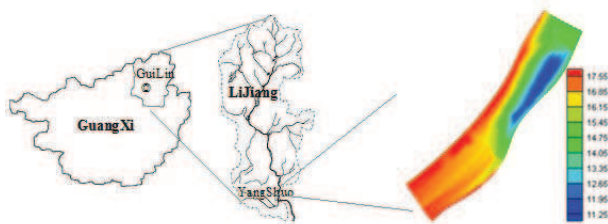

Figure 2. The case study area (reference elevation: 86.4m)

Data collection. The hydrological data during 1958-2004 were collected from the Yangshuo hydrological station, including cross-section geometry, daily averaged discharge, water level, and some water quality parameters. In addition, the historical survey records of the aquatic vegetation were collected as well from the local agency and universities. Since the reservoir started water recharge in dry season from 1987 and the focus

was to investigate the impact of reservoir regulations, two typical hydrological years before and after 1987 were selected for study (Table 1).

Table 1. Typical hydrologic years (*even year, p=50%*)

pre-operation	post-operation	$\bar{R}$	C_V	C_S/C_V
1976	1999	40.59	0.21	2.0

Field survey was conducted with concerns on both physical and biological features. The bathymetry and the flow profiles of the studied river section were measured by the Doppler flow measurement device River Cat (SonTek/YSI). In total, 15 cross-sections were measured and the data for the entire area were obtained by interpolation. About the vegetation condition, 10 sites were surveyed in each side along the river section. In each site, five points that formed an 'S' shape were sampled and each point had a size of 1m × 1m. Three herbs were identified as the dominant species in the studied area, including two typical telmatophytes (wetland species), *Rumex maritimus* and *Polygonum hydropiper*, and one terriphyte (terrestrial species) *Leonurus heterophyllus*. The number and the dry weight of the three typical species were counted at each site.

Table 2. Empirical values for the parameters of the vegetation model

Items	R. maritimus	P. hydropiper	L. heterophyllus
Seed weight	0.0002g	0.002g	0.0002g
Max. growth rate	0.13	0.12	0.13
Max. biomass per plant	2.70g	1.65g	3.00g
Inundation			
Biomass loss rate	0 [a]	0.02/d	/ [b]
Mortality rate	0.05/d (i.d.>40 days) [c]	0.025/d (i.d.>10 days)	0.8/d (i.d.>5 days)
Drought			
Growth rate decrease	63% (d.d. >5 days) [d]	27% (d.d.>15 days)	0
Mortality rate	0.05/d (d.d.>10 days)	0.05/d (d.d.>20 days)	0

[a] "0" indicates no biomass loss but not normal growth; [b] *L. heterophyllus* suffers great biomass loss during inundation, with an assumed mortality rate of 0.1~0.2/d during short period of inundation; [c] i.d. : inundation duration; [d] d.d. : drought duration.

The physiological parameters of each species were obtained from experiments (e.g. Figure 3) and existing literatures . Table 2 lists some important parameters used in the vegetation model.
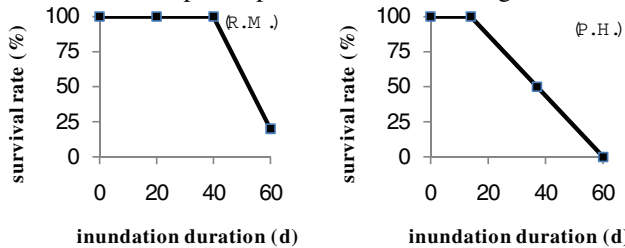

Figure 3. Response curve of *R. maritimus* (left) and *P. hydropiper* (right) to inundation stress

Boundary condition for hydrodynamic module. Daily averaged discharge was applied at the upstream boundary and daily averaged water level was applied at the downstream boundary. The simulation time step was 1.5 minutes and the output data was daily averaged water depth and velocity in each grid. The bottom boundary condition was specified as $(\tau_{bx}, \tau_{by}) = \rho_0 C_{Db} \sqrt{u_b^2 + v_b^2} \cdot (u_b, v_b)$, where τ is the bottom stress, C_{Db} is the bottom drag coefficient, which can be expressed as $C_{Db} = g n_b^2 / R_s^{1/3}$, where n_b is the Manning coefficient

corresponding to the bed roughness, and R_s is the hydraulic radius of the bed. Calculation of n_b from field observation was adapted from Cowan (1956). The parameters that reflect channel geometry were neglected because they've been explicitly taken into account by the quasi-3D model. For the present model, the specified roughness coefficients of different bed materials are listed in Table 3.

Table 3. Empirical values for bottom roughness (Manning's n)

Stream bed	0.035	Earth with *scarce* riparian plant	0.035
Exposed cobble bed on flood plain	0.035	*medium* riparian plant	0.045
Cobble ground with scarce riparian plant	0.040	*dense* riparian plant	0.060

Vegetation evolution rules. The main rules for the cellular automata module were specified below:

(1) Germination: in riparian zone, seeds germinate along with the recession of the first flood after winter dormancy. Due to relatively high dispersal ability and long dormancy of herbaceous seeds, the compositions of herbaceous seed banks were assumed evenly distributed and abundant. 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 were scattered evenly in the simulation space.

(2) Growing period: the juvenile plants are most prone to adverse environment and disturbances . The susceptibility (or tolerance) differs among the species (Table 1), which contributes to the differentiation of distribution along the water level gradients. *R. maritimus* and *P. hydropiper* are typical riparian species, while *L. heterophyllus* is not adapted to inundation and commonly appears on higher land where floods seldom reach.

(3) Mature period: mature plants of the three species show much more tolerance to adverse environment. They are all able to survive in 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 winter, and seeds have a loss rate.

(5) The local interactions and species competitions were formulated according to the field survey and lab experiments. The general idea was that the resource of a given grid was limited, and if the plants growing in a particular grid exceed the carrying capacity, competition and colonization take place. Suppose that the resources of per

Table 4. 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	
L. heterophyllus	Normal growth	Keep growing at the cost of other species [a]	Colonize neighbors	Stop growing
P. hydropiper & *R. maritimus*	Normal growth	Colonize neighbors [a]	Colonize neighbors	Stop growing

[a] 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*.

unit area is $R = 1$ (resources/m^2), and the resource consumption of species "i" is $C_i = S / (n_i \times M_{\max}^{i})$, where S is the area of sample site, n_i is the number of the species i under optimal conditions in the sample site, M_{max}^{i} is the maximum biomass of an individual species i under optimal conditions. Taking *R. maritimus* for example, the filed survey found that in the most suitable environment, the $n_i = 3$ and $M_{max}^{i} = 2.7$, so correspondingly $C_i = 1/(3\times2.7)$. Therefore, the available resource of the cell k is defined as

$$R_k = 1 \cdot S - \sum_{i=1}^{n} \left(C_i \times B_i^k \right) - \sum_{neib=1}^{3} \sum_{i=1}^{n} \left(C_i \times B_i^{neib} \right)$$

where, R_k is the available resource in cell k, B_i^k is the biomass of species "i" in cell k, 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 4.

RESULTS

Figure 4 presents the modelled water level of the three scenarios that were pre-operation year 1976, post-operation year1999 with water recharge (1999WR) and no recharge (1999NR). Water level was considered as the most important factor which affects the growth of riparian plants. Compared to the scenario 1999NR, the averaged water level was increased for 1999WR, especially in the dry seasons from October to next March. Since the slope of the floodplain is mild, slight variation of water level could lead to the shifting of dry-wet of a large region, which directly affect plant growth.
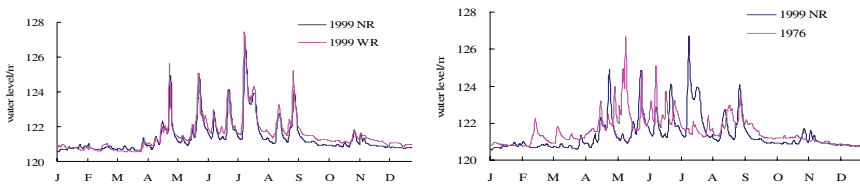

Figure 4. Water level variations of different scenarios (left: 1999NR vs. 1999WR; right: 1999NR vs. 1976).

Figure 5 showed the modelled vegetation patterns of the three scenarios, where the plant biomass was depicted by pixels of different colors. The distribution of *R. maritimus* and *P. hydropiper* in 1976 was significantly wider than in 1999. Meanwhile, *L. heterophyllus* which is more susceptible to flood but more tolerant to drought expanded toward the main stream and colonized the habitat previously occupied by *R. maritimus* and *P. hydropiper*. In general, the modelled trend was consistent with the observations and the results obtained by statistical niche models, and the difference was mainly caused by the river regulation.

Figure 6 showed the mean biomass of each species in different elevation band, i.e. the vertical gradient of the vegetation. Because the absolute weight of each species had large difference, relative biomass which was the proportion to the maximum plant biomass was used for illustration instead of the absolute biomass. The value then lied between 0 and 1, where 1 indicated the best growth. *R. maritimus* appeared close to the water line, and the mean biomass approached to the peak at an elevation a little higher than the base flow. As the elevation increases, *R. maritimus* disappeared gradually due to drought stress and competition from terriphytes. *P. hydropiper* followed a similar trend as *R. maritimus*, but the peak appeared at a higher elevation due to the difference of flood-tolerance. *L. heterophyllus* flourished in the orthofluvial zone where floods seldom reached.

The effect of water recharge in dry season was also investigated in the study and the results were present in Figure 5 and Figure 6. The similar trend was perceived that the water recharge in dry season had negative effects on *R. maritimus* and *P. hydropiper*, while it was advantageous to *L. heterophyllus*. However, the impacts were not significant.

The modelled results in Figure 7 showed that *R. maritimus* and *P. hydropiper* flourished in the frequently disturbed condition, but barely survived under steady flow condition. It is consistent with the previous findings that frequent fluctuation of water level may exclude phreatophytes species like *L. heterophyllus* and favorites hygrophytes such as *R. maritimus* and *P. hydropiper* (Hill and Keddy 1992; Keddy and Reznicek 1982). The main reason lies in the severe competition pressure and drought stress in the steady condition.

For example, Keddy (e.g. 1989) proposed some hygrophytes could also grow well in the shrub zone but are usually prevented by the stronger competitors (phreatophytes) in that area. Figure 8 presents the modelled results of a scenario in which the more competitive terriphyte *L. heterophyllus* were artificially excluded. It was seen that after the terriphyte 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 of pattern was directly related to the alleviated competition pressure from the terriphytes.
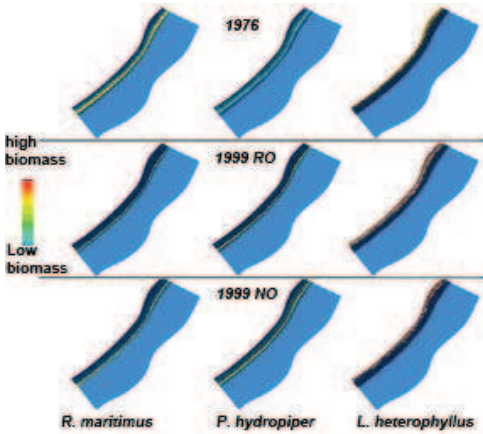

Figure 5. The distribution pattern of the modelled three scenarios.
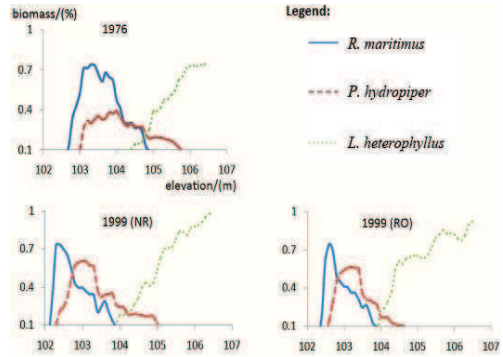

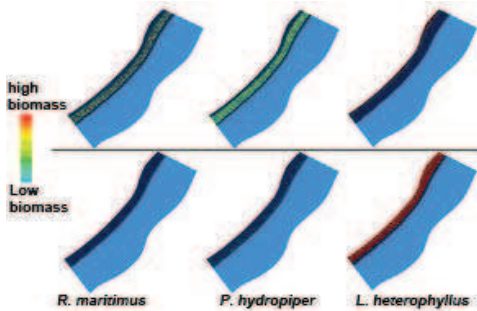Figure 6. The vertical gradient of relative biomass of the modelled three scenarios.

Figure 7. The distribution pattern of three species in the hypothesized scenario (top: frequent water level fluctuation; bottom: steady condition)
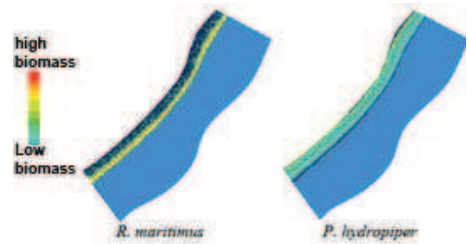

Figure 8. The distribution pattern of *R. maritimus* and *P. hydropiper* in the hypothesized scenario that *L. heterophyllus* was removed

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

DISCUSSIONS

Cellular automata approach had demonstrated the efficiency in modelling of riparian vegetation dynamics. Some essential processes in riparian plant communities had been successfully captured, such as plant life cycle, plant response to flow conditions, intra- and interspecies competition. Cellular automata also showed its

compatibility with other numerical simulation techniques, such as finite-volume or finite-element based hydrodynamic simulation. The integrated framework is critical in identifying the interrelating processes of riparian system.

The major difficulty for most of the spatially-explicit modelling is the requirement of detailed background information. Huge amount of plant species are present in a watershed, 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 the conventional statistical models. In statistical models, plant species are surveyed and grouped according to their niche preferences. Such "functional group" (Hill et al. 1998) 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 modelling of a large scale may be realized.

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