

# Modelling the riparian vegetation evolution due to flow regulation of Lijiang River by unstructured cellular automata

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## ABSTRACT

The flow regulation of rivers, mainly for flood control in wet season and water supply in dry season, dramatically altered the hydrological regime in the downstream, thus imposed significant impacts on the aquatic ecosystem. The evolution of riparian vegetation is an important indicator to quantify these impacts. This research focuses on the understanding of the vegetation dynamics and succession of riparian zones due to flow regulations by reservoir operation. The study developed an integrated model which couples a two-dimensional hydrodynamics module with a vegetation evolution module. Owing to the ability to well present spatial heterogeneity and local interactions, the vegetation module applied a cellular automata approach. To more precisely describe the complex morphology and topography, and to improve computation efficiency, an unstructured cellular automata (UCA) scheme which implemented a triangular mesh was used. The developed model was applied to a typical compound channel of the Lijiang River, which has been largely affected by the flow regulations of the Qingshitan reservoir for navigation purpose. The model was calibrated by the historical vegetation data, the field observations and the controlling experiment data. Through the scenarios simulation, the effects of flow regulation on riparian vegetation dynamics were analyzed. In addition, the potentials of UCA in riparian vegetation modelling were well explored.

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## 1. Introduction

Riparian zone, a transitional area between aquatic and terrestrial systems, is characterized by large environmental gradients and multiple interrelating processes. The highly dynamic system supports diverse plant communities due to the flow fluctuations of different intensities at different scales (Costanza et al., 1997; Whiting, 2002; Hironobu et al., 2003; Tomlinson and d'Carlo, 2003). The state of riparian vegetation, in particular shrubs and herbs, is sensitive to disturbances of environmental conditions, even a slight change of hydrological regime. River regulations, such as dam construction, flow diversion and water withdrawal, have significantly altered the flow regimes and consequently reshaped the riparian patterns (Dynesius and Nilsson, 1994; Naiman et al., 2005; Nilsson et al., 2005; Shi and Jiao, 2007). Compared to natural variations, these anthropogenic disturbances are generally more dramatic and often exert debilitating effects on plant communities (Naiman et al., 2005). Thus, knowledge on how a riparian plant community response to human induced alterations is needed to preserve the biodiversity and protect the endangered species (Lin and Wang, 2002).

In the last decades, the ecological value of riparian vegetation has been increasingly recognized. Great efforts have been made to better

understand the spatial pattern and evolution mechanism of riparian plant communities. Different types of models have been developed to assess and predict the impacts of river regulations on riparian plants. Among these approaches, statistical models were first and also widely used (e.g. Franz and Bazzaz, 1977; Hill and Keddy, 1992; Toner and Keddy, 1997; Hill et al., 1998). The fundamental idea of such kind of models is to establish a relation between particular plant species to key environmental factors. Without exploring deep into the underlying mechanism of riparian dynamic processes, the statistical models greatly reduced the complexity of the problem. These models serve as a convenient and practical way to predict vegetation patterns when scenarios are analyzed.

The advantage of statistical method consists in the static feature. In these models, the sampled and predicted vegetation patterns are assumed in “quasi-equilibrium”. In the case of some highly dynamic systems, such equilibrium may be hard to find. Furthermore, these models only provide snapshots at each equilibrium, while the processes from one equilibrium to another are treated in a black-box. However, sometimes the information about how the system evolves from one state to another is important, especially when implement restoration programs. To better understand a riparian system and its underlying processes, process-based methods are demanded.

Process-based models present a more continuous view of riparian dynamics basing on historical plant establishment requirements and channel evolution features. The interactions between morphology change and vegetation succession was taken into account as well

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(Merritt and Cooper, 2000;). But these models were mostly aggregated that failed 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 were explored (Chen et al., 2002; Perry and Enright, 2007; Chen and Ye, 2008; Chen et al., 2009a). The conventional cellular automata models applied structured grids, either square (Chen et al., 2002), or triangular or hexagon (Trunfio, 2004; Birch et al., 2007). However, real studied regions usually have very complex morphology and topography. Besides, most ecosystems exhibit irregular patchiness (Aassine and Jaï, 2002; Blackwell, 2007). Therefore, unstructured cellular automata scheme has been adopted to ecosystem simulations (Chen and Ye, 2008; Chen et al., in press), which can also improves the computation efficiency.

In this study, a riparian vegetation module was developed using unstructured cellular automata, and then integrated with a hydrodynamic module. 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 2006–2008 were used for model calibration and verification. Both realistic and hypothesized scenarios were simulated to quantify the impacts of flow regulations on the riparian vegetation evolution. Meanwhile, the potential of this kind of model was largely explored, and the pros as well as cons of spatially-explicit approach were discussed.

**2. Method**

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

**2.1. Hydrodynamic module**

The hydrodynamic module used the two-dimensional shallow water equations that are given below.

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

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

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

where,  $Q_a$  is discharge or withdrawal ( $m^3/s$ ),  $H$  is water level (m),  $u, v$  are velocity in  $x$  and  $y$  direction (m/s),  $\nu$  is horizontal eddy viscosity coefficient ( $m^2/s$ ),  $f$  is Coriolis parameter, and  $\tau_x, \tau_y$  are bottom shear stress (N/m).

The stability requirement of multi-dimensional problem was rather strict, thus implicit scheme was used to stabilize the numerical solution. To reduce the band of coefficient matrix in the implicit

scheme, the alternating direction iterations (ADI) method was applied (Lu and Guan, 2004).

**2.2. Riparian vegetation module**

The spatially-explicit approach, 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 and Sole, 2000; Chen et al., 2002; Chen, 2004).

In the vegetation module, the studied area was discretized into a triangular mesh. When properly configured, a smooth transition between cells of different sizes can be achieved, which facilitated local refinement (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 morphology.

A set of evolution rules has 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 can be drawn from field investigation, controlled experiments, and expert empirical knowledge.

**2.3. Model integration**

The hydrodynamic module and the vegetation module were integrated to simulate the riparian vegetation changes due to flow regulations. Considering the computation load and daily irradiance, it was logic to define the time step of vegetation module as 1 day, and this time scale was used for the integrated model. However, the time step of hydrodynamic module was mostly much smaller because of the request from numerical stability and simulation accuracy. For two-dimensional model with implicit scheme, the Crout number (Cr) was usually less than 10. Therefore, the outputs (water level and velocity) of the hydrodynamic module were daily averaged. At each step, the vegetation module read the averaged values from the hydrodynamic module and calculated the influence on the local plants. It is well known that in hydrodynamic model, the velocity was calculated at the nodes and the depth was calculated in the centre of each grid. In cellular automata model, the calculation was based on cell, and the state was represented by the value in the centre. Therefore, the averaged velocity of the nodes was used. In such a way, the two modules were integrated in spatial and temporal domain.

**3. Case study in Lijiang River**

**3.1. Study site**

The developed model was applied to the compound channel near the Yangshuo station of the Lijiang River, which is located in the Southwest China (Fig. 2). Due to the special Karst landscape and the strong seasonality of rainfall, the discharges at the Yangshuo station vary from  $12 m^3/s$  to  $12,000 m^3/s$  with an annual average of  $120 m^3/s$ . The recorded minimum discharge was  $8 m^3/s$ , which imposed great threats to the local water supply and aquatic ecosystem. More important, the tourism is the predominant income of the local economy. When the discharge is lower than  $30 m^3/s$  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 hits the local economy. Therefore, a series of reservoirs has 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  $60 m^3/s$ . 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 on

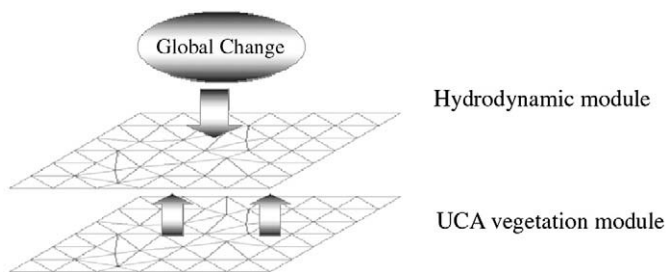


Fig. 1. The model framework.

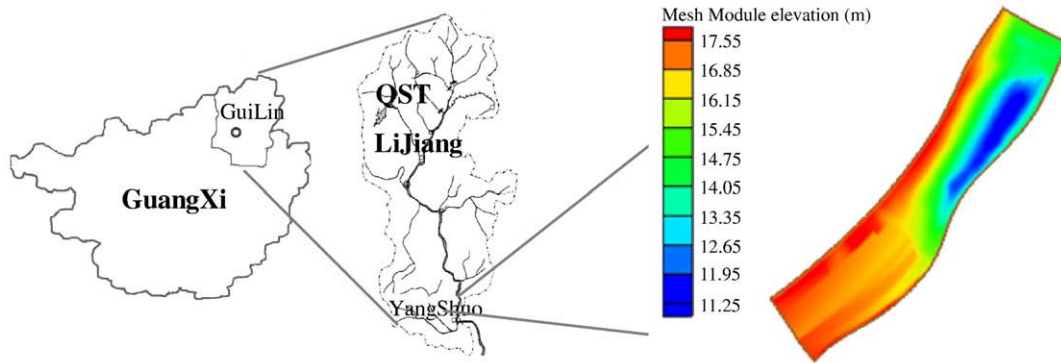


Fig. 2. The case study area (reference elevation: 86.4 m).

the downstream aquatic ecosystem and then seek for 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., 2009b) and riparian vegetation successions presented in this paper.

3.2. 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 to recharge water 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).

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, which is manufactured by the 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 1 m×1 m. Three herbs were identified as the dominant species in the studied area, including two typical hygrophyte species *Rumex maritimus* and *Polygonum hydropiper*, and one phreatophyte specie *Leonurus heterophyllus*. The number and the dry weight of the three typical species were counted in each point.

The physiological parameters of each species were collected from laboratory controlling experiments (e.g. Fig. 3) and the existing literatures (Timson, 1965, 1966; Mitchell, 1976; Carter and Grace, 1990; Vandersman et al., 1993a,b; Nabben et al., 1999). Table 2 listed some important parameters used in the vegetation module.

3.3. Initial and boundary condition

For the hydrodynamics module, daily averaged discharge was applied at the upstream boundary and daily averaged water level was applied at the downstream boundary. The initial velocity was set to 0 and the initial water level was set so that the entire riverbed was submerged. The simulation time step was 15 min, and the computed

Table 1  
Typical hydrologic years.

	Even year pre-operation (p=50%)	Even year post-operation (p=50%)	$\bar{R}$	$C_v$	$C_s/C_v$
Year	1976	1999	40.59	0.21	2.0

water levels as well as velocities were daily averaged for the vegetation module.

For the vegetation module, open boundary was applied to the water side, and fixed boundary (Chen, 2004) was used for the other three sides. The initial condition was started from seed, which was assumed saturated in each grid.

3.4. Vegetation evolution rules

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

- (1) Germination: in riparian zone, seeds germinated 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 were most prone to adverse environment and disturbances (Vartapetian and Jackson, 1997). The susceptibility (or tolerance) differed among the species (Table 1), which contributed to the differentiation of distribution along the water level gradients. *R. maritimus* and *P. hydropiper* were typical hygrophyte species, while *L. heterophyllus* was not adapted to inundation and mostly appeared on the upper land where floods seldom reach.
- (3) Mature period: mature plants of the three species showed much more tolerance to adverse environment. They all were able to survive in longer inundation or drought stress, and the survival rates were similar. The seeds were produced in this period.
- (4) Winter loss: all the annual herbaceous plants died in the winter, and the seeds had 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,

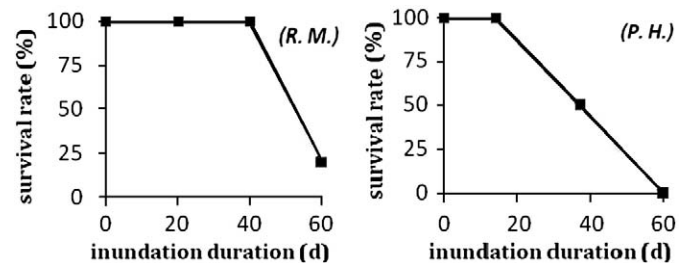


Fig. 3. Response curve of *R. maritimus* (left) and *P. hydropiper* (right) to inundation stress.

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

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>a</sup>	0.02/d	/ <sup>b</sup>
Mortality rate during inundation	0.05/d (i.d.>40 days) <sup>c</sup>	0.025/d (i.d.>10 days)	0.8/d (i.d.>5 days)
Growth rate decrease during drought	63% (d.d.>5 days) <sup>d</sup>	27% (d.d.>15 days)	0
Mortality rate during drought	0.05/d (d.d.>10 days)	0.05/d (d.d.>20 days)	0

<sup>a</sup> "0" indicates no biomass loss but not normal growth.  
<sup>b</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>c</sup> i.d.: inundation duration.  
<sup>d</sup> d.d.: drought duration.

and if the plants growing in the grid exceed the capacity, competition and colonization took place. Supposing the resources of per unit area was  $R=1$  (resources/m<sup>2</sup>), the resource consumption of species "i" was

$$C_i = S / (n_i \times M_{max}^i) \tag{4}$$

where  $S$  is the area of sample site,  $n_i$  is the number of the species  $i$  under optimal conditions in the sample site, and  $M_{max}^i$  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 the corresponding  $C_i=1/(3 \times 2.7)$ . Therefore, the available resource of the cell  $k$  was defined as:

$$R_k = 1 - \sum_{i=1}^n (C_i \times B_i^k) - \sum_{neib=1}^3 \sum_{i=1}^n (C_i \times B_i^{neib}) \tag{5}$$

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 were illustrated in Table 3.

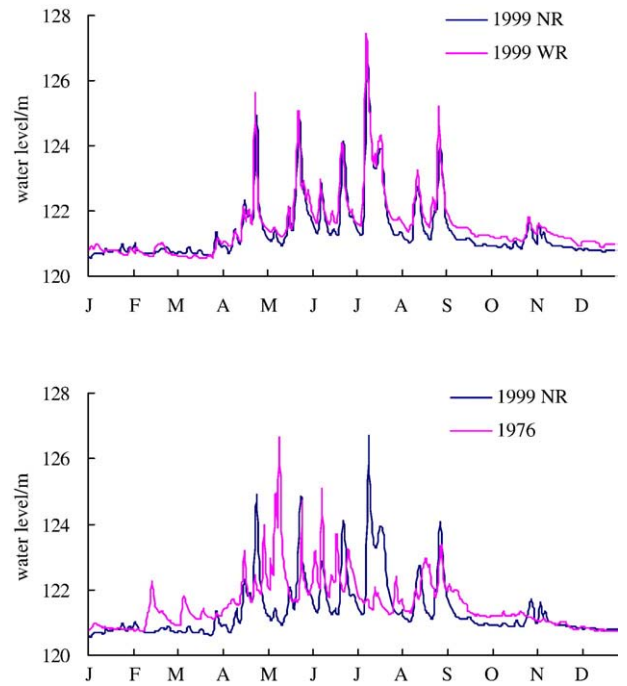
**4. Results**

Fig. 4 presented the modelled water level of the three scenarios that were pre-operation year 1976, post-operation year 1999 with water recharge (1999WR) and no recharge (1999NR). Water level was considered as the most important factor which affected the growth of riparian plants. Compared to the scenario 1999NR, the averaged water level was increased for 1999WR, especially in the dry season 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 affected the water plants growth.

**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 <sup>a</sup>	Search for neighboring resources	Stop growing
<i>P. hydropiper</i> and <i>R. maritimus</i>	Normal growth	Search for neighboring resources <sup>a</sup>	Search for neighboring resources	Stop growing

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



**Fig. 4.** Water level variations of different scenarios (top: 1999NR vs. 1999WR; bottom: 1999NR vs. 1976).

Fig. 5 showed the modelled vegetation patterns of the three scenarios, where the plant biomass was depicted by pixels in 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 with the results obtained by statistical niche models, and the difference was mainly caused by the river regulation.

Fig. 6 showed the mean biomass of each species in different elevation band, i.e. the vertical gradient of the species distribution. 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 front, and the mean biomass approached to the peak at an elevation a little higher than the base flow. As the elevation increased, *R. maritimus* disappeared gradually due to the drought stress and the competition from phreatophyte species. *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 upland zone where floods seldom reached.

The effects of water recharge in dry season were also investigated in the study and the results were present in Figs. 5 and 6. The similar trend was perceived that the water recharge in dry season had negative effects

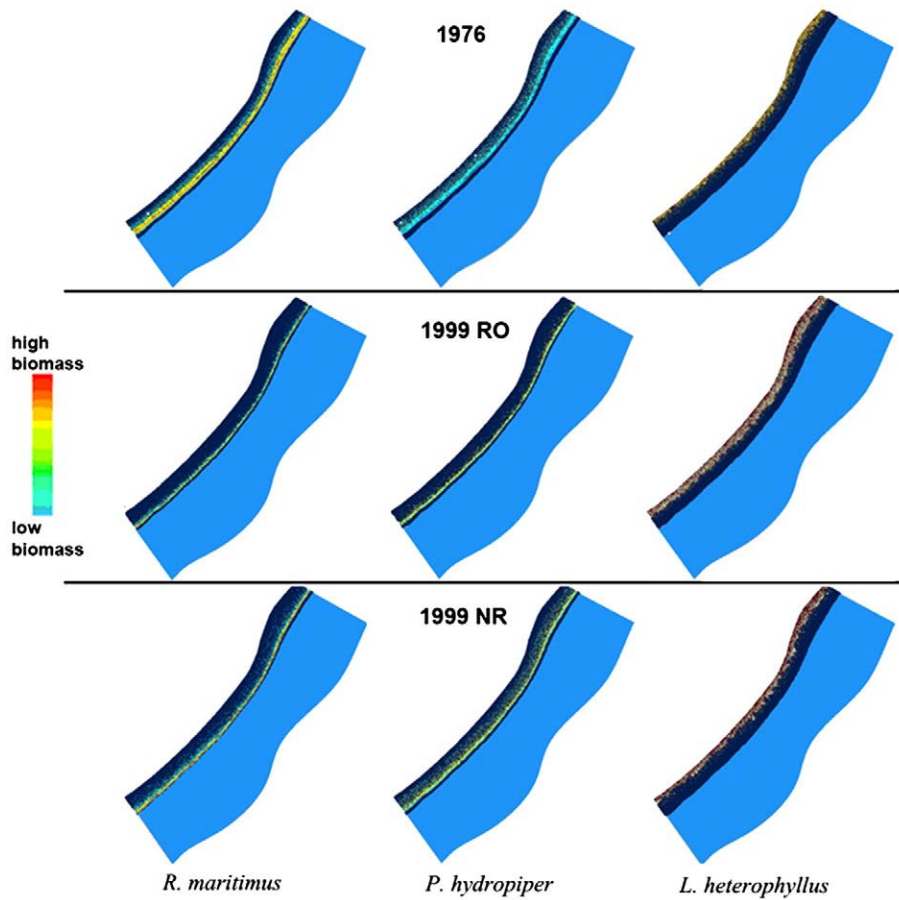


Fig. 5. The distribution pattern of the modelled three scenarios.

on *R. maritimus* and *P. hydropiper*, while it was advantageous to *L. heterophyllus*. However, the impacts were not significant.

The modelled results in Fig. 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 phreatophyte species like *L. heterophyllus* and favorites to hygrophytes such as *R. maritimus* and *P. hydropiper* (Keddy and Reznicek, 1982; Hill and Keddy, 1992). The main reason lies in the severe competition pressure and drought stress in the steady condition.

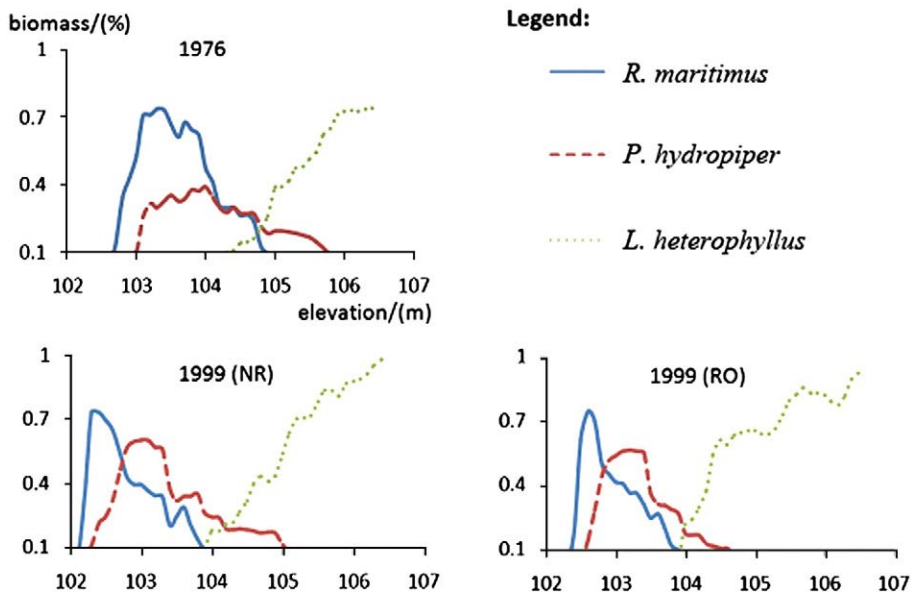


Fig. 6. The vertical gradient of relative biomass of the modelled three scenarios.

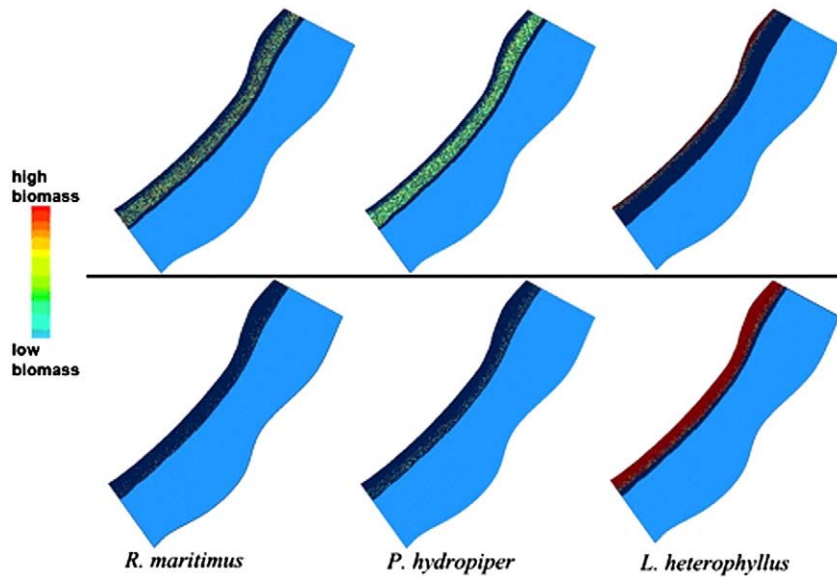


Fig. 7. The distribution pattern of three species in the hypothesized scenario (top: frequent water level fluctuation; bottom: steady condition).

It had been recognized that not only the abiotic processes affected the plant distribution, but the interspecies competition played another important role (Grime, 1973; Keddy, 1985; Wilson and Keddy, 1986; Day et al., 1988; Keddy, 1989; Goldberg and 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) argued that some hygrophyte species could also grow well in the shrub zone but were usually prevented by the stronger competitors from phreatophyte in that area. The Fig. 8 presented the modelled results of a scenario in which the more competitive phreatophyte species *L. heterophyllus* were artificially excluded. It was seen that after the phreatophyte species was removed, the habitat range of *R. maritimus* and *P. hydro Piper* spread landward, which was consistent with the existing theories and field experiments. The change of pattern was directly related to the relieved competition pressure from the phreatophyte 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 *P. hydro Piper* that usually habitat in the dry–wet transition zone. The modified flow regime seemed to favor the phreatophyte species *L. heterophyllus* to expand towards the river, thus gradually colonized the space previously occupied by *R. maritimus* and *P. hydro Piper*. Because dry–wet transition zone 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 environ-

ment 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.

### 5. 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 condition, intra- and interspecies competitions. Cellular automata also showed its compatibility with other numerical simulation techniques, such as finite-volume or finite-element methods. Through the manipulation in space (grids/cells) and time, the continuous formulation of PDEs (partial differential equations) and the discrete formulation of CA were integrated, so that the effects of flow alternations on vegetation evolutions were well investigated.

It was seen that the modelled river section had very complex morphology and topography. There is a deep zone in the bottom-right area and an irregular shoal in the top-right area. This shoal provides the foundation for plants to establish, thus the accurate description of the shape is very important to model the vegetation pattern. The study showed that unstructured grid has ultimate advantages to achieve it. It was also observed that UCA was more computational efficient, except that programming was somehow harder.

The major difficulty for most of the spatially-explicit modelling is the requirement of detailed background information. A large 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” (e.g. 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 modelling of a large scale may be realized.

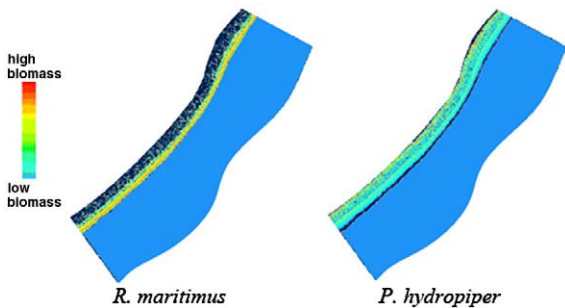


Fig. 8. The distribution pattern of *R. maritimus* and *P. hydro Piper* in the hypothesized scenario that *L. heterophyllus* was artificially removed.

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## References

- Aassine, S., Jaï, M.C.E., 2002. Vegetation dynamics modelling: a method for coupling local and space dynamics. *Ecological Modelling* 154, 237–249.
- Alonso, D., Sole, R.V., 2000. The DivGame Simulator: a stochastic cellular automata model of rainforest dynamics. *Ecological Modelling* 133, 131–141.
- Birch, C.P.D., Oom, S.P., Beecham, J.A., 2007. Rectangular and hexagonal grids used for observation, experiment and simulation in ecology. *Ecological Modelling* 206, 347–359.
- Blackwell, P.G., 2007. Heterogeneity, patchiness and correlation of resources. *Ecological Modelling* 207, 349–355.
- Blanch, S.J., Ganf, G.G., Walker, K.F., 1999. Tolerance of riverine plants to flooding and exposure indicated by water regime. *Regulated Rivers-Research & Management* 15, 43–62.
- Carter, M.F., Grace, J.B., 1990. Relationships between flooding tolerance, life history, and short-term competitive performance in three species of *Polygonum*. *American Journal of Botany* 77, 381–387.
- Chen, Q., 2004. Cellular Automata and Artificial Intelligence in Ecohydraulics Modeling. Taylor & Francis Group plc, London UK.
- Chen, Q., Ye, F., 2008. Unstructured cellular automata and the application to model river riparian vegetation dynamics. *Lecture Notes in Computer Science* 5191, 337–344.
- Chen, Q., Mynett, A.E., Minns, A.W., 2002. Application of cellular automata to modelling competitive growths of two underwater species *Chara Aspera* and *Potamogeton Pectinatus* in Lake Veluwe. *Ecological Modelling* 147, 253–265.
- Chen, Q., Ye, F., Li, W., 2009a. Cellular automata based ecological and ecohydraulics modeling. *Journal of Hydroinformatics* 11 (3–4), 252–265.
- Chen, Q., Cheng, Z., Han, R., Wang, H., 2009b. An integrated water quality and individual based model to study the impacts of reservoir operations on downstream fish dynamics. *Proceeding of the 33rd IAHR Congress, Vancouver, Canada*, pp. 6198–6205.
- Costanza, R., d'Arge, R., Groot, R., Farber, S., Grasso, M., Hannon, B., 1997. The value of the world's ecosystem services and natural capital. *Nature* 387, 253–260.
- Day, R.T., Keddy, P.A., McNeill, J., Carleton, T., 1988. Fertility and disturbance gradients—a summary model for riverine marsh vegetation. *Ecology* 69, 1044–1054.
- Dynesius, M., Nilsson, C., 1994. Fragmentation and flow regulation of river systems in the northern 3rd of the world. *Science* 266, 753–762.
- Franz, E.H., Bazzaz, F.A., 1977. Simulation of vegetation response to modified hydrologic regimes—probabilistic model based on niche differentiation in a floodplain forest. *Ecology* 58, 176–183.
- Goldberg, D.E., Barton, A.M., 1992. Patterns and consequences of interspecific competition in natural communities — a review of field experiments with plants. *American Naturalist* 139, 771–801.
- Grime, J.P., 1973. Competitive exclusion in herbaceous vegetation. *Nature* 242, 344–347.
- Hill, N.M., Keddy, P.A., 1992. Prediction of rarities from habitat variables — coastal-plain plants on Nova Scotian lakeshores. *Ecology* 73, 1852–1859.
- Hill, N.M., Keddy, P.A., Wisheu, I.C., 1998. A hydrological model for predicting the effects of dams on the shoreline vegetation of lakes and reservoirs. *Environmental Management* 22, 723–736.
- Hironobu, S., Varawoot, V., Whitaker, A.C., 2003. Stochastic flow duration curves for evaluation of flow regimes in rivers. *Journal of the American Water Resources Association* 39, 47–58.
- Hupp, C.R., Osterkamp, W.R., 1996. Riparian vegetation and fluvial geomorphic processes. *Geomorphology* 14, 277–295.
- Keddy, P.A., 1985. Lakeshore plants in the Tusket River Valley, Nova Scotia: the distribution and status of some rare species including *Coreopsis rosea* and *Sabatia kennedyana*. *Rhodora* 87, 309–320.
- Keddy, P.A., 1989. Effects of competition from shrubs on herbaceous wetland plants: a 4-year field experiment. *Canadian Journal of Botany* 67, 708–716.
- Keddy, P.A., Reznicek, A.A., 1982. The role of seed banks in the persistence of Ontario coastal-plain flora. *American Journal of Botany* 69, 13–22.
- Li, R., Chen, Q., Mynett, A.E., Wu, S., Wang, H., 2008. Modelling of the flow changes due to reservoir operations and the impacts on aquatic ecosystem downstream. *Proceedings of the 16th IAHR-APD Conference, Nanjing, China, Vol. VI*, pp. 2272–2278.
- Lin, Z.S., Wang, S.G., 2002. Study on the relations between the animal species extinct ion and habitat destruction. *Acta Ecologica Sinica* 22, 535–540.
- Lu, J., Guan, Z., 2004. Numerical Solution of Partial Differential. Tsinghua University Press, Beijing.
- Merritt, D.M., Cooper, D.J., 2000. Riparian vegetation and channel change in response to river regulation: A comparative study of regulated and unregulated streams in the Green river basin, USA. *Regulated Rivers* 16, 543–564.
- Mitchell, R.S., 1976. Submergence experiments on nine species of semi-aquatic *Polygonum*. *American Journal of Botany* 63, 1158–1165.
- Nabben, R.H.M., Blom, C., Voesenek, L., 1999. Resistance to complete submergence in *Rumex* species with different life histories: the influence of plant size and light. *New Phytologist* 144, 313–321.
- Naiman, R.J., Décamps, H., McClain, M., 2005. Riparia—Ecology, Conservation, and Management of Streamside Communities. Elsevier/Academic Press, San Diego.
- Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the world's large river systems. *Science* 308, 405–408.
- Perry, G.L.W., Enright, N.J., 2007. Contrasting outcomes of spatially implicit and spatially explicit models of vegetation dynamics in a forest-shrubland mosaic. *Ecological Modelling* 207, 327–338.
- Shewchuk, J.R., 2002. Delaunay refinement algorithms for triangular mesh generation. *Computational Geometry—Theory and Applications* 22, 21–74.
- Shi, X., Jiao, T., 2007. Analysis and control of impacts of water discharge during large dam operation on the downstream ecosystem. *Water Conservancy Science and Technology and Economy* 13, 320–323.
- Timson, J., 1965. Germination in *Polygonum*. *New Phytologist* 64, 179–186.
- Timson, J., 1966. *Polygonum Hydropiper* L. *Journal of Ecology* 54, 815–821.
- Tomlinson, S.M., d'Carlo, H.E., 2003. The need for high resolution time series data to characterize Hawaiian streams. *Journal of The American Water Resources Association* 39, 113–123.
- Toner, M., Keddy, P., 1997. River hydrology and riparian wetlands: a predictive model for ecological assembly. *Ecological Applications* 7, 236–246.
- Trunfio, G.A., 2004. Predicting wildfire spreading through a hexagon cellular automata model. In: Sloot, P.M.A., Chopard, B., Hoehstra, A.G. (Eds.), *Lecture Notes of Computer Sciences*, 3305, pp. 385–394.
- Vandersman, A.J.M., Blom, C., Barendse, G.W.M., 1993a. Flooding resistance and shoot elongation in relation to developmental stage and environmental-conditions in *Rumex-Maritimus* and *Rumex-Palustris*. *New Phytologist* 125, 73–84.
- Vandersman, A.J.M., Joosten, N.N., Blom, C., 1993b. Flooding regimes and life-history characteristics of short-lived species in river forelands. *Journal of Ecology* 81, 121–130.
- Vartapetian, B.B., Jackson, M.B., 1997. Plant adaptations to anaerobic stress. *Annals of Botany* 79, 3–20.
- Whiting, P.J., 2002. Stream flow necessary for environmental maintenance. *Annual review of Earth and Planetary Sciences* 30, 181–206.
- Wilson, S.D., Keddy, P.A., 1986. Measuring diffuse competition along an environmental gradient: results from a shoreline plant community. *American Naturalist* 127, 862–869.