# Unstructured Cellular Automata and the Application to Model River Riparian Vegetation Dynamics

Qiuwen Chen and Fei Ye

State Key Lab for System Ecology, Research Centre for Eco-Environmental Sciences, Chinese Academy of Sciences, China
{qchen,fye}@rcees.ac.cn

**Abstract.** Cellular automata (CA) have proved to be a robust approach to spatially-explicit modeling of ecosystems. Conventionally the CA models applied a structured square grid. However, due to the anisotropic properties of environmental conditions, the capability of CA method was not fully explored when using the regular squared lattice. This research investigated the unstructured cellular automata (UCA) by implementing a irregular triangular grid and used it to develop a vegetation dynamics model. The model was then coupled with a two-dimensional hydrodynamic model to simulate the riparian vegetation dynamics due to flow modifications by the reservoirs operations. The integrated model was 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 simulations, the previous evolutions of the riparian vegetations were recaptured and their future developments under the new flow regulation scheme were predicted. In particular, the potentials of UCA in ecosystem modeling were illustrated in the research.

## 1 Introduction

Cellular automata constitute a mathematical system, in which the simple local components interact together to produce global complicated dynamics. Cellular automata have become a viable alternative approach to ecological modelling [1, 2], in particular after the emergence and application of object-oriented programming language.

Conventionally cellular automata models apply a structured grid, for example the regular squared lattice. However, ecosystems are mostly characterised by the spatial anisotropy [3, 4], which indicates that some important local variations might be lost in these models. Although, the hexagon grid had been investigated [5, 6], they are still structured. Besides, they have not been widely used in the ecological models.

The riparian zones are highly dynamic systems governed by interrelating physical and biological processes. The physical template of riparian zone is characterized by several typical geomorphic features, mainly including channel bed, channel shelf, floodplain and terrace [7]. Plant communities of different characteristics are distributed along the river side according to the ecological gradients. However, it is challenging to model the riparian successions, especially when flow patterns are largely modified by river regulations, for instance, the reservoir operations.

H. Umeo et al. (Eds): ACRI 2008, LNCS 5191, pp. 337–344, 2008.

Some previous attempts to this subject include the use of cellular automata approach [1, 8]. However, these studies all applied a squared grid, thus some key local features such as turbulence intensity and microscopic topography of riverbed were not well presented. The simulated spatial vegetation patterns on the shoals and floodplains are different from the surveys.

This research developed an UCA model for vegetation dynamics by implementing the irregular triangular grid and integrated it with a two-dimensional hydrodynamic model. The integrated models were applied to simulate the impacts of flow modifications on riparian vegetation evolutions. The following sections will illustrate the development and application of the UCA model through a case study.

## 2 Study Site

The Lijiang River is a famous tourism resort in Southwest China. The flow in the river has dramatic seasonal fluctuations that can reach 12000 $m^3/s$ in rainy season and down to only $12m^3/s$ in dry season. For decades, river regulations have been implemented to ameliorate the flows for tourism cruise. Several reservoirs have been constructed or under construction in the main stem and branches. 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 and will be further modified by reservoir operation, it is important to quantitatively evaluate the influences on the downstream ecosystem.

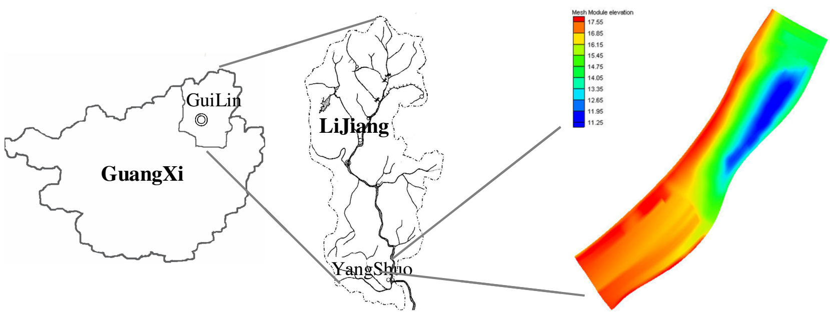


**Fig. 1.** Study site and the channel bed elevation

The study selected a typical compound channel in the downstream of the Lijiang River near the Yangshuo hydrological station, where the influences of all the upstream reservoirs can be perceived (Fig. 1). Field survey was conducted with concerns on both physical and biological features.

## 3 Model Development

### 3.1 Model Framework

To deal with the multiple processes described above, an integrated model is developed. The model framework is illustrated in Fig. 2 where the flow and vegetation dynamics are solved by hydrodynamic module and UCA vegetation module respectively. The "global change" in Fig. 2 may be caused by either natural or anthropogenic influences, such as river regulations.

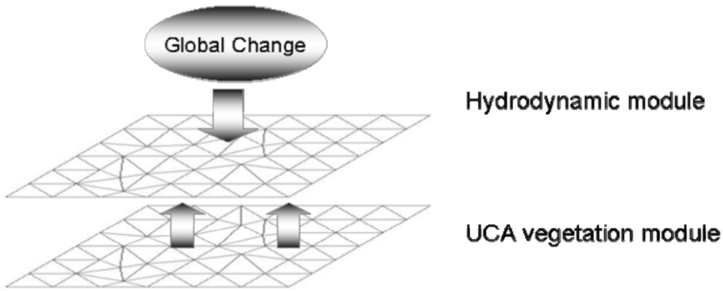


**Fig. 2.** The framework of the integrated hydrodynamic and UCA model

### 3.2 Hydrodynamic Module

The hydrodynamic model solves the depth-integrated equations (1-3) of fluid mass and momentum conservation in two horizontal directions.

$$h\frac{\partial u}{\partial t}+hu\frac{\partial u}{\partial x}+hv\frac{\partial u}{\partial y}-\frac{h}{\rho}\left[E_{xx}\frac{\partial^2 u}{\partial x^2}+E_{xy}\frac{\partial^2 u}{\partial y^2}\right]+gh\left[\frac{\partial a}{\partial x}+\frac{\partial h}{\partial x}\right]+\frac{gun^2}{h^{1/3}}\left(u^2+v^2\right)^{1/2}=0 \quad (1)$$

$$h\frac{\partial v}{\partial t}+hu\frac{\partial v}{\partial x}+hv\frac{\partial v}{\partial y}-\frac{h}{\rho}\left[E_{yx}\frac{\partial^2 v}{\partial x^2}+E_{yy}\frac{\partial^2 v}{\partial y^2}\right]+gh\left[\frac{\partial a}{\partial y}+\frac{\partial h}{\partial y}\right]+\frac{gvn^2}{h^{1/3}}\left(u^2+v^2\right)^{1/2}=0 \quad (2)$$

$$\frac{\partial h}{\partial t}+h\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}=0 \quad (3)$$

In which: $h$-water depth, $u$, $v$ - velocities in the Cartesian directions, $x$, $y$, $t$ - Cartesian coordinates and time, $\rho$ - density of fluid, $E$ - Eddy viscosity coefficient, $g$ - acceleration due to gravity, a - elevation of bottom, n - Manning's roughness.

The boundary conditions were defined using the data from the Yangshuo hydrological station. Daily averaged discharge was applied at the upstream boundary and daily averaged water level was applied at the downstream boundary. The finite element method (FEM) was applied to solve the equations numerically. The simulation time step is 15minutes and the output data is daily-averaged in order to consist with the time step of vegetation module. Six scenarios were simulated that are high, even and low flows for with and without reservoir regulations respectively.

### 3.3 Vegetation Module

Three annual herbs that are *Rumex Maritimus* (*R. Maritimus*), *Polygonum Hydropiper* (*P. Hydropiper*) and *Leonurus Heterophyllus* (*L. Heterophyllus*) were investigated on the channel shelf. The annual herbaceous species were selected in the present study because they complete their life cycle in relatively short time. Field data were collected to reflect the present distribution patterns of these species.

The physical template of the riparian zone is represented by a UCA grid, with physical and biological properties specifying bed morphology and vegetation condition. The simulated plants can "grow" by updating cell properties at every time step. The updating rules are based on several dominant processes of the plant's life cycle. External forcing was introduced by reading the output of hydrodynamic module. The characteristics of each species are obtained from experiments and existing literatures. Table 1 gives the parameters used in the vegetation model. The typical responses of the modelled species to the inundations are presented in Fig 3.

**Table 1.** Empirical values for the parameters of the vegetation module

| Items | *R. Maritimus* | *P. Hydropiper* | *L. Heterophyllus* |
|---|---|---|---|
| Seed weight | 0.0002g | 0.0002g | 0.0002g |
| Max. growth rate | 0.13 | 0.12 | 0.13 |
| Max. biomass per plant | 2.70g | 1.65g | 3.00g |
| Biomass loss rate during inundation | 0 * | 0.02/d | / ** |
| Mortality rate during inundation | 0.05/d (i.d. >40 days) *** | 0.025/d (i.d.>10 days) | 0.8/d (i.d.>5 days) |
| Growth rate decrease during drought | 63% (d.d. >5 days) **** | 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 |

Note: (*) "0" indicates no biomass loss but not normal growth; (**) *L. Heterophyllus* suffers great biomass loss during inundation, with an assumed mortality rate of 0.1~0.2/d during short period of inundation; (***) i.d.: inundation duration; (****) d.d.: drought duration.

Based on these parameters, the vegetation dynamics were simulated in a UCA grid with main concerns on the flow disturbances during the growing season. The main CA rules are illustrated bellow: (1) Germination: in riparian zone, seed germination takes place along with the recession of the first floods after winter dormancy. Due to relatively high dispersal ability and long dormancy of herbaceous seeds, the compositions of herbaceous seed banks are similar in different areas of a riparian zone and abundant [9]. 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, and the amount of geminated seeds is equal to the maximum number of mature plants allowed in a cell.

(2) Growing period: the juvenile plants are most prone to adverse environment and disturbances. The susceptibility (or tolerance) differs among the species, which contributes to the species differentiation along the water level gradients. *R.Maritimus* and *P.Hydropiper* are typical riparian species, while *L.Heterophyllus* is not adapted to inundation and mostly presents on the upper land where floods seldom reach.

(3) Mature period: mature plants of the three species show much more tolerance to adverse environment. 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 a loss rate.

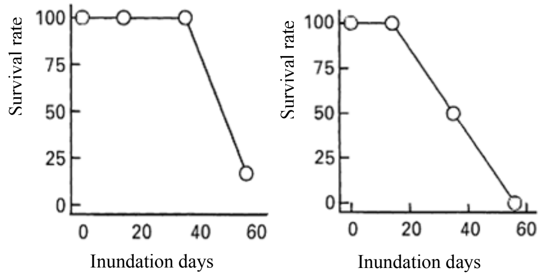


**Fig. 3.** Response curve of *R. Maritimus* and *P. Hydropiper* to inundation stress

(5) The local interactions and species competitions are formulated according to the field survey and lab experiments. Suppose that the resources of per unit area is R=1 (resources/$m^2$), and the resources consumption of species *i* is $c_i = S/(n_i \times M^i{}_{\max})$, where *S*-area of sample site, *n*-the number of the species *i* under optimal conditions in the sample site, $M_{max}$ - the maximum biomass of an individual species *i* under optimal conditions. Taking *R. Maritimus* for example, the filed survey found that the $n$ =3 and $M_{max}$ =2.7, so the corresponding $C_i$ = 1/(3×2.7). Therefore, the available resource of the cell *k* is defined as:

$$R_k = 1 - c_i \times B_i^k - c_i \times B_i^n \tag{4}$$

where the $R_k$ – available resource in cell *k*, $B_i^k$ -is the biomass of species *i* in cell *k*, $B_i^n$ -is the biomass of species *i* colonizing the cell *k* from the neighbors. If $R_k$ >0, all species grow normally. Otherwise, two different options are defined: if *L. Heterophyllus* have not reached to the saturated biomass, *L. Heterophyllus* keeps normal growth due to the strong competition capability, while *R. Maritimus* and *P. Hydropipr* decrease. If *L. Heterophyllus* have reached to saturated biomass, it will colonise if there is available resources in the neighbours, or it will sustain saturation.

*R. Maritimus* and *P. Hydropipr* follow the similar rules as *L. Heterophyllus* except that they can only utilise the remained resources due to their low competition capability. In reality, *R. Maritimus* and *P. Hydropipr* hardly reach to saturated level.

The simulation time step of the CA based vegetation model is 1 day. The model reads the outputs (water level and velocity) from the hydrodynamic module and calculates its influence on the plants growth. Although only the water level and flow velocity were taken into account in the present vegetation module, other variables such as water quality could also be incorporated in the similar way.

# 4 Model Results

## 4.1 Hydrodynamic Model Outputs

Fig. 4 shows the daily variations of water levels with and without the reservoir operations in the typical dry year (2004, post-dam).

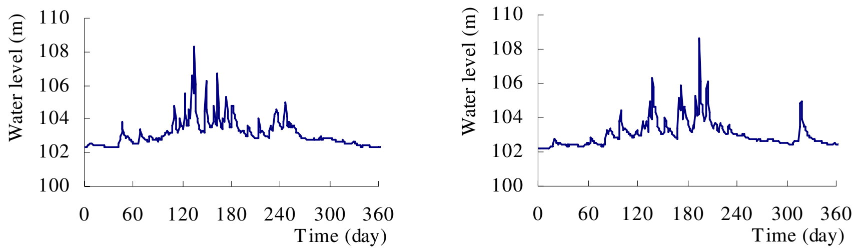


**Fig. 4.** Water levels in typical dry year without (left) and with (right) regulations

Without the reservoir regulation, the floods were frequent and intense, with high peak water level, but relatively short duration of single flood. Under the reservoir regulation, the flood frequency and intensity decreased, but the recession of flood is slower, resulting in prolonged duration of single flood event. Fig 5 is the snapshot of the simulated water depth during low flow and high flow periods within a year. The unsubmerged area of the channel shelf during low flow period provides the habitat for vegetation establishment.

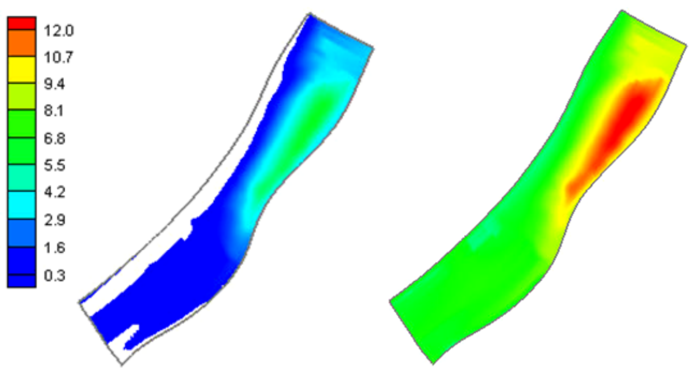


**Fig. 5.** Flow patterns during base flow (left) and high flow (right) seasons

## 4.2 Vegetation Model Outputs

Fig. 6 shows the comparisons of the species distributions with and without reservoir regulations in the typical dry year (2004, post-dam). From the results, the changes of distribution could be perceived. Without flow regulation, the habitat ranges of *R. Maritimus* and *P. Hydropiper* were significantly wider than with regulations. When river regulation was implemented, they both shrunk largely. At the same time, *L. Heterophyllus*, which is more susceptible to flood and tolerant to drought, expanded toward the river side and colonized the habitats that were previously occupied by the *R. Maritimus* and *P. Hydropiper*. The results are in general consistent with both the observations and the statistical niche models.

Fig.7 shows the elevation averaged biomass of each species along the transect. The “elevation averaged biomass” refers to the average biomass of all the plants growing on the same elevation. Because the absolute weights of the species are significantly different, the relative biomass was used instead. The relative biomass was defined as

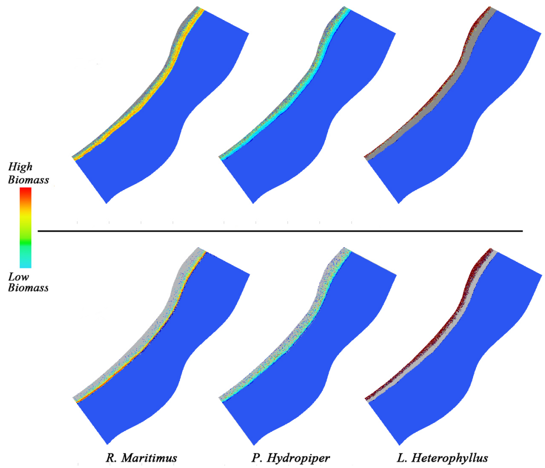


**Fig. 6.** Species distribution in dry year for without (top) and with (bottom) regulations

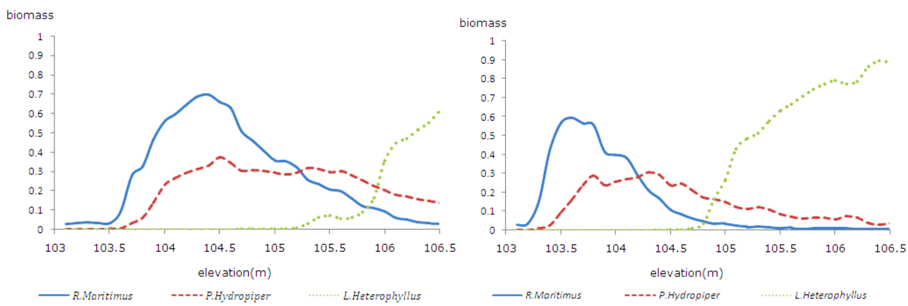


**Fig. 7.** Species gradients in dry year for without (left) and with (right) regulations

the proportion of average biomass to maximum biomass of a single mature plant. The values are then in between 0 and 1.

As a semi-aquatic species, *R. Maritimus* mainly grow in the area close to the river bank. The peak biomass appears in the strip with an elevation a little higher than the water level under base flow. As the elevation increases, the species disappears gradually for the drought stress and the competition from upland species. The distribution of *P. Hydropiper* has a similar pattern as *R. Maritimus*, but the peak biomass appears at a higher elevation because of the difference of flood tolerance. *L. Heterophyllus* start to appear near the peak biomass of *P. Hydropiper* and become dominant gradually at higher elevation where floods can seldom reach.

After the reservoir operation, the distribution of *R. Maritimus* shrunk, but the peak biomass has not been strongly affected. However, *P. Hydropiper* suffered a significant decrease in both the distribution and the peak biomass. Comparing to *R. Maritimus*, *P. Hydropiper* is less tolerant to flood inundation, and it consumes more stored carbohydrate during inundation. But on the other hand, it does require frequent flood disturbances to support the competition with the upland species *L. Heterophyllus*. Therefore, after reservoir operation, less flood frequency and longer flood duration made the riparian habitat less suitable for the growth of *P. Hydropiper*. *L. Heterophyllus* obviously benefits from the flow modification, with an expanded habitat range and an increased peak biomass.

## 5 Discussions

The research demonstrated that UCA approach is powerful to implement spatial anisotropy and local interactions that are critical to understand riparian ecosystem. In the developed model, the microscopic riverbed topography was well represented by the UCA grid. The species local interactions were implemented at multiple levels, including internal interactions such as competitions and colonisations among the plants, and external interactions between the species and the flow conditions.

Although there are many factors influencing riparian vegetation dynamics, it is impractical and unnecessary to incorporate all of them into the model. The seed dynamics and the flow disturbances during juvenile period had been identified as the key processes of the vegetation models [3, 7, 9]. They determine whether a species is able to establish and its chance to survive after establishment. When the plants become mature, they are less susceptible to adverse environment except for prominent disturbances such as destructive high flows and extremely long inundation duration.

## Acknowledgement

The research is funded by National Nature Science Foundation of China (50639070).

## References

1. Chen, Q., Mynett, A.E., Minns, A.W.: Application of cellular automata to modelling competitive growths of two underwater species Chara aspera and Potamogeton pectinatus in Lake Veluwe. Eco. Mod. 147, 253–265 (2002)
2. Perry, G.L.W., Enright, N.J.: Contrasting outcomes of spatially implicit and spatially explicit models of vegetation dynamics in a forest-shrubland mosaic. Eco. Mod. 207, 327–338 (2007)
3. Aassine, S., Jaï, M.C.E.: Vegetation dynamics modelling: a method for coupling local and space dynamics. Eco. Mod. 154, 237–249 (2002)
4. Blackwell, P.G.: Heterogeneity, patchiness and correlation of resources. Eco. Mod. 207, 349–355 (2007)
5. Birch, C.P.D., Oom, S.P., Beecham, J.A.: Rectangular and hexagonal grids used for observation, experiment and simulation in ecology. Eco. Mod. 206, 347–359 (2007)
6. Trunfio, G.A.: Predicting wildfire spreading through a hexagon cellular automata model. In: Sloot, P.M.A., Chopard, B., Hoekstra, A.G. (eds.) ACRI 2004. LNCS, vol. 3305, pp. 385–394. Springer, Heidelberg (2004)
7. Hupp, C.R., Osterkamp, W.R.: Riparian vegetation and fluvial geomorphic processes. Geomorphology 14, 277–295 (1996)
8. Chen, Q., Ye, F., Li, R.: Modelling of the Riparian Vegetation Dynamics due to Reservoir Operations through an Integrated Cellular Automata. In: IAHR 2008, Nanjing, China (2008)
9. Schneider, R.L., Sharitz, R.R.: Seed bank dynamics in a South-eastern riverine swamp. American Journal of Botany 73, 1022–1030 (1986)