Effects of riverbed deformation on the dynamic modeling of riparian vegetation succession and its application for river management

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Abstract

Recently, riparian zone of East Asian rivers are intensively forested, which provides a number of problems in the river management especially at the downstream of dams (Asaeda *et al*. 2012, 2015a). One of the major causes is likely the reduction of sediment in the river channel. Hence, sediment bypass tunnels, which transport sediment from the upstream to the downstream reach of a dam, may have a potential to reduce impacts of the structure in the channel. Under this background, a dynamic riparian vegetation model (DRIPVEM) is developed to predict the colonization and succession of vegetation in a river channel, aiming to predict the vegetation succession in the downstream of a sediment bypass tunnel (Asaeda *et al*. 2012b, Sanjaya and Asaeda 2017). After the validation on the vegetation succession with observed data using measured morphological data of several rivers, then the model is combined with the 2-dimensional river bed deformation model, and is applied to the targeted river (i.e. Kuzuryugawa (river) in Fukui, Japan) to obtain the effects of the morphological change of the river channel on the vegetation patterns after a flood. The comparison of trials with and without the bed deformation model indicated that morphological change during the flood period has a substantial effect on the vegetation pattern after a flood. Furthermore, simulations were conducted for the future condition of vegetation, showing possible wide applications of the present model for river management works.

Keywords: *Salix* spp., vegetation succession, nitrogen cycle, geomorphological change, river management

1 Introduction

Subjected to frequent and strong flood disturbances, sediment bars and floodplains are often composed of sand and stones, which provide unique habitats for organisms (Sakio 1997). However, river regulation and flow controls cause a huge encroachment of herbaceous and woody plants, then reduce the particular ecological functions of the floodplain. Compared to herbaceous plants, woody plant communities, though they are sometimes washed away at floods, have stronger resistance against the flood flow, and have a serious problem in flood control management (Asaeda *et al*. 2010).

In these days, riparian zone of East Asian rivers, especially downstream of dams, are intensively forested, which provides a number of problems (Jamil *et al*. 2014). The development of prediction tools for forestation is, therefore, particularly requested.

Unlike the primary succession of terrestrial vegetation from herbs to trees, vegetative succession on the riparian zone is far complex due to frequent flood disturbances associated with the colonization and flushing of vegetation at the flood time (Junk and Piedade 1997). Compared to the biological model, the simulation of geomorphological change takes an extremely longer period, thus, the application of the surveyed results of the channel morphology is one of possibilities for the vegetation simulation. However, the difference from the case of combined simulation with geomorphology must be evaluated beforehand. This study targets to elucidate the difference in the plant distribution simulation results with and without the simulation of the channel morphology.

2 The structure of the simulation model

An individual based mechanistic model, Dynamic Riparian Vegetation Model (DRIPVEM) was developed to predict the vegetation distribution and succession of the riparian area (Asaeda *et al*. 2015b, Sanjaya and Asaeda 2017). The model includes 4 modules, hydrological condition, tree, herb and soil nitrogen to describe the material flows and the influences between each group as follows, and Fig. 1 shows the model structure.

The Hydraulic module provides the water level of a target river. In the Tree module, trees are recruited at species-specific elevation relative to water level with species-specific initial density, at suitable flooding in the seed dispersion season. Then, each individual tree grows following the empirically obtained species- and organ-specific allometric functions, while their density is gradually minimized by self-thinning (Asaeda *et al*. 2010). Then, at a succeeding flood, a part of them are flushed away based on the erosion depth, following the species- and tree age-specific flushing function. In the Herb module, herb biomass is given by the functions of soil nitrogen content, sediment size as a parameter of moisture content, and shading effects of neighboring trees. Because of the relatively shallow root systems of herbs, they need a sufficient amount of moisture and nutrients, particularly nitrogen, in the surface sediment layer (Asaeda *et al*. 2012).

Nitrogen cycle of the surface sediment is given externally by the sum of atmospheric fallout, nitrogen fixation, denitrification, and deposition and flushing by flooded water, and internally by the uptake by plants, and decomposition of aboveground herb biomass and defoliated tree leaves. All these processes are modeled using other module results or provided by meteorological observatories.

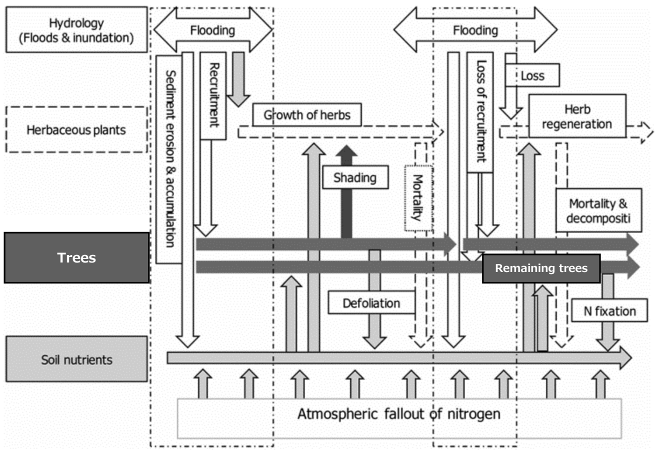

Fig. 1: Schematic diagram of the model structure

3 Simulation process

In the simulation of geomorphological process, a model was developed to simulate the 2-dimensional flow and the geomorphological change of the channel. For the river bed deformation solver, Nays2DH of the iRIC (International River Interface Cooperative) package (Shimizu *et al*. 2012), composed of Iwagaki formula to calculate critical stress at river bed and Ashida-Michiue formula to simulate the bedload transport, is used.

The time scale of channel deformation, which occurs during floods, is much less than that of biological processes, and due to their highly non-linear processes, 0.1 sec time step was used to calculate the flood flow, the sediment transport rate and the geomorphological changes, compared to 30–31 days of time step used for the biological processes.

The simulation was conducted for Morita district, 20–22 km from the river mouth of Kuzuryugawa (river), Fukui, Japan. General curvilinear coordinate system and quadrilateral mesh size of about 10 m × 10 m were used in the simulation and the total mesh number was 6510.

The result of geomorphological simulation (i.e. water surface elevation, geometry of river bed and mean diameter of sediments etc.) was employed at every time step of biological simulation conducted by DRIPVEM.

Fig. 2 shows the annual largest flow rates at Nakatsuno observatory, and indicates that there was a relatively large flood, 2500 m^3/s, in 2006, in Kuzuryu River, compared to the average flow rate of 1750 m^3/s.

We assumed no vegetation condition on the sand bar at 2006 as the initial condition, and vegetation patterns were simulated from 2006 to 2012. Then, the results were compared to the observation obtained from aerial photo images to validate the model.

Two types of simulations were conducted to evaluate the effect of geomorphological change during the flood on the vegetation colonization. In the 1st simulation, geomorphological changes caused by floods was not taken into account. The 2nd simulation was conducted by the model combined with geomorphological changes during the flood.

In the field observation conducted before the simulation, mean diameter of sediments was obtained as about 45 mm. Main tree species om the sediment bar were *Salix* spp. at lower area and *Juglans mandshurica* at higher area, and *Humulus japonicas* were the dominant herbs.

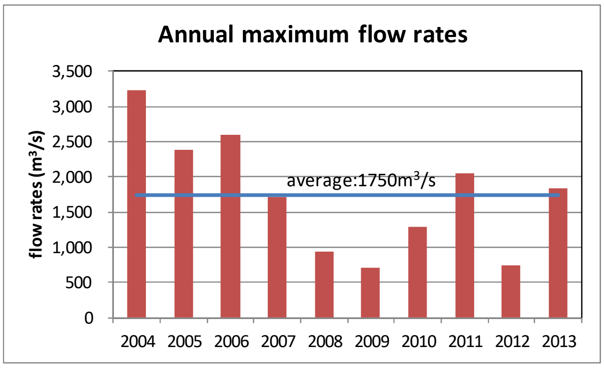

Fig. 2: Annual maximum flow rates at Nakatsuno observatory in Kuzuryugawa (river)

4 The comparison of the simulation with and without geomorphological simulation

Generally sufficient agreement was achieved at least as a management level, whether combined with the simulation of the geomorphological changes or not.

Salix community on the sand bar, which was practically important, was suitably simulated in both cases, in spite of a slight difference.

Fig. 3 shows that the distribution of *Salix* community simulated together with the geomorphological changes. The distribution of *Salix* area was only 5% larger compared with aerial photos. In addition, the high density area of *Salix* spp. was successfully reproduced. While, without the geomorphological simulation, the *Salix* community area was 93% of the observation, and high *Salix* density sites on the sandbar was not reproduced.

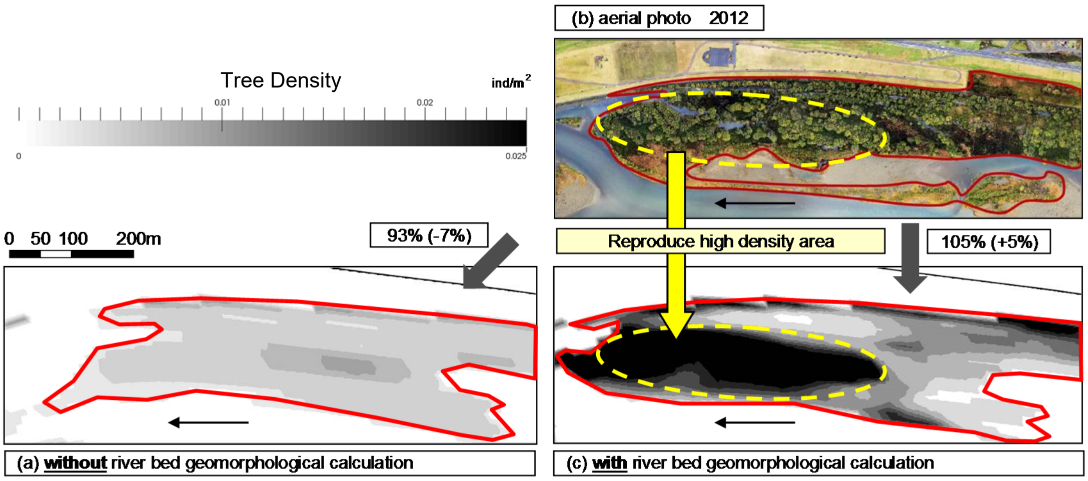

Fig. 3: The difference of simulated results of DRIPVEM between with and without geomorphological simulation

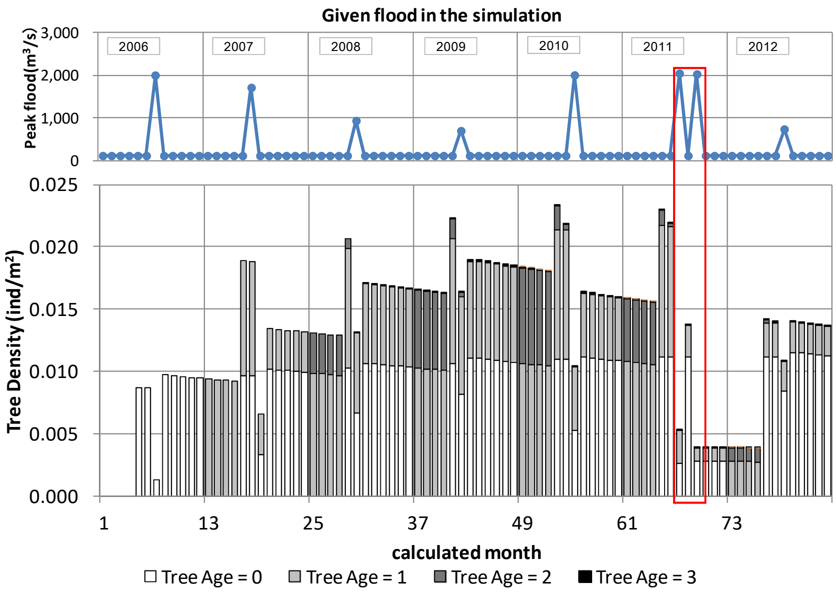

Fig. 4: The time series variation of the age-specific density of *Salix* trees on the sandbar

The flushing of *Salix* trees was more suitably obtained by the geomorphological simulation for each year flood, especially in 2011, as shown in Fig. 4.

5 Application to the river management

For an application to the management of the river, we used the model to simulate the future condition of vegetation for 10 years after 2012, where the next 10 year flood pattern was assumed to be same as that of the previous 10 years.

In addition that *Salix* trees make a suitable biological environment of the riparian zone, they also become a barrier against the flood flow and sometimes fall. The felling of trees is one of the possible processes to reduce the number of trees. Therefore, we examined the effect of *Salix* felling at floods. The assumed frequencies of *Salix* felling are shown in Tab. 1. Case-A is as control where there is no *Salix* felling. In Case-B, *Salix* felling is carried out in November of the second year. In addition, in Case-C, we assumed the *Salix* felling on the sand bar to be once every 3years.

Table 1: *Salix* felling cycle of Case- A, B & C

Case name	Frequency of *Salix* felling	Implementation year(s)
Case-A	- (No *Salix* felling)	-
Case-B	1time / 10year	2nd
Case-C	1time / 3year	2nd , 5th , 8th

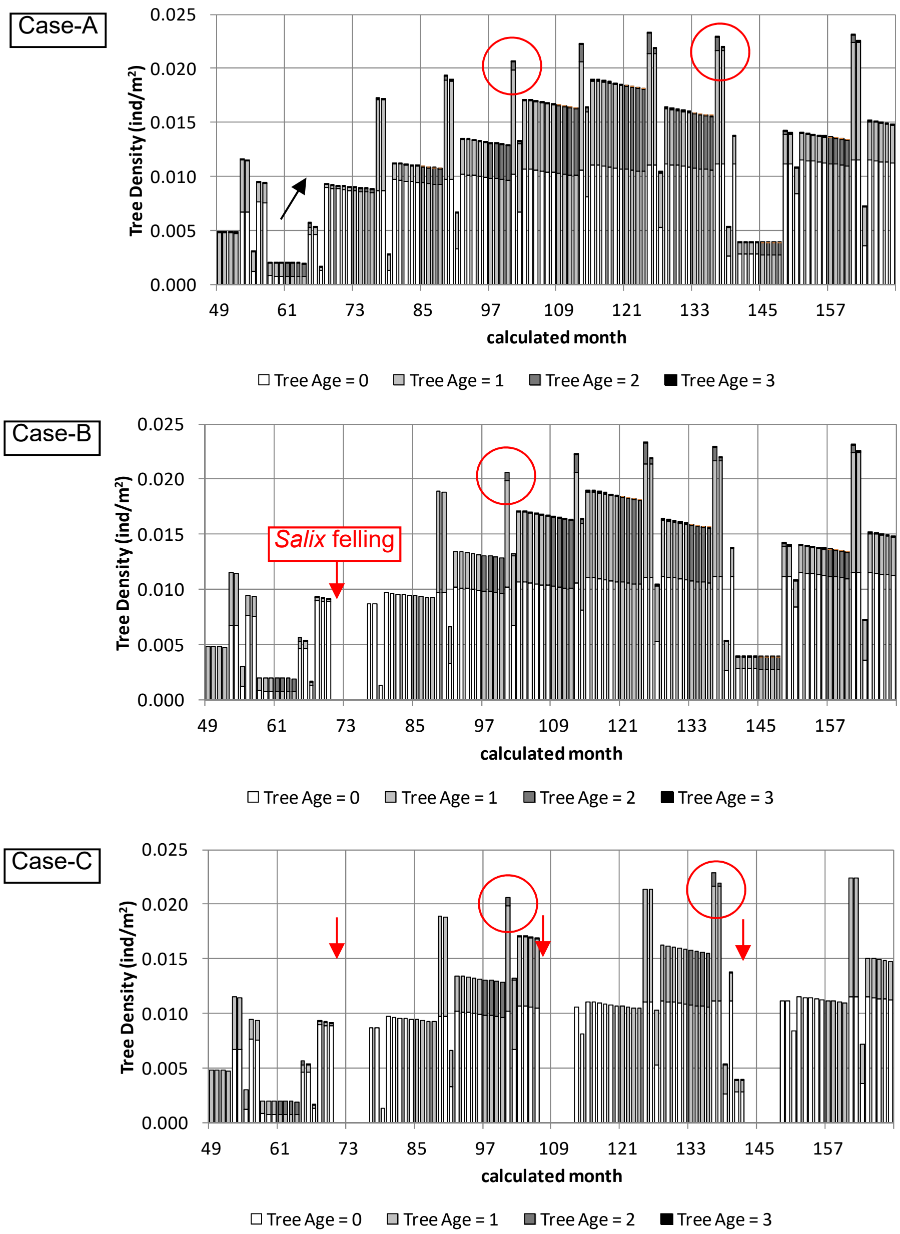

Fig. 5: The time series variation of the age-specific density of *Salix* trees on the sandbar in Case-A, B & C

Fig. 5 shows the calculated results. In Case-B, the density of *Salix* trees remains low in the following years after *Salix* felling, it is restored to the same level to that of Case-A in the next 3 years. In Case-C, the tendency of the max density of *Salix* is preserved to the same level of Case-A.

Therefore, it may be difficult to suppress the invasion of *Salix* by felling, because *Salix* seeds are supplied to the shoreline and germinate every year in this sandbar under the present hydrological condition.

6 Conclusions

A dynamic mechanistic vegetation model, DRIPVEM, was employed to simulate the vegetation and geochemical succession of the midstream riparian area. The model was combined with the 2-dimensional dynamic model to simulate the change in the channel bed morphology. Then the effect of the application of the geomorphological simulation was evaluated. It was found that in general the succession of tree distribution in the following years was relatively well simulated by the combination of DRIPVEM model and surveyed geomorphological data.

However, more accurate results were obtained if the simulation of geomorphological change of the sandbars is employed. For the practical application, therefore, the geomorphological simulation during the flood period is also desirable, although it takes longer time for the simulation.

The combined model, then, can simulate the effect of hydrological changes and the various treatment of river management on the vegetation succession in the following years.

The present study indicates the possible wide application of the present model in the management of rivers including sediment bypass tunnels.

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