A numerical approach on the modelling of nutrient dynamics and vegetation succession in midstream sediment bars of a regulated river

1. Introduction

Flood disturbance is one of the major causes of tree mortality either by inundation or erosion on a sediment bar. It also changes the morphological conditions of riparian zone as well as disturbs habitats on the sandbar.

However, with the absence of large floods and presence of suitable germination condition, some sandbars become heavily colonized by vegetation following the process of primary vegetation succession [3]. Due to this, sand and gravel areas are vanishing and this causes environmental and flooding problems as it becomes an obstruction for flood flow and damages the river bank [2].

Efficient forest management is based on forecasts of the effects of forest operations [5] and numerical analysis tools had proved to be a suitable method to tackle this issue. Several numerical models were proposed in order to describe vegetative succession of sediment bars [2], however, most of the models have not mentioned in-depth about the dynamic process such as flood influence on colonization and succession with respect to nutrient cycle etc., thus, Asaeda et al. (2012) had developed a dynamic model [1, 3] which can predict the vegetation succession and amount of nutrient processed by herbaceous plants and trees on a sediment bar during an interval of large floods.

Based on that, the purpose of the present study is (1) to create a numerical analysis program-based tool, and (2) to verify the model by comparing the simulated results with the observe data to investigate whether they have mutual agreement.

2. Materials and Methodology

(1) Model structure

Fig. 1 shows the schematic diagram of the model which includes the hydrology, tree growth, herbaceous and the nutrient cycle sub-model and how it relates to each other. The hydrology sub-model includes tree flushing effects trees and herbaceous plants either by erosion or inundation and determines the
survival ratio of trees and herbaceous plant.

In this model, allometric relations (using parameters such as tree age and diameter breast height) are used to predict the growth of trees. Herbs biomass equations are with respect to particle size, soil nitrogen and tree canopy shading effects.

The decomposition of tree leaf litter and dead herbaceous species release nitrogen to the sediment whereas biomass processes from trees and herbs, uptake nitrogen from the sediment.

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**Fig.1. Model Framework**

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1. **Tree sub-model components**

   a) Recruitment

   Seeds can be dispersed by wind, animals (feces etc.) as well as flood.

   This model was developed to suit the vegetation in riparian areas. Majority of riparian trees are hydrochorious and disperse seeds at flood time while they are tolerant to low nutrient condition (Nilsson C *et al.*, 2010.).

   In order for colonization to occur, flood must happen at the exact period of the season.

   

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Initial density</td>
<td>30/m²</td>
<td>0.3/m²</td>
</tr>
<tr>
<td>Effective floods</td>
<td>May</td>
<td>August-September</td>
</tr>
<tr>
<td>Elevation range</td>
<td>1-3m</td>
<td>3-6m</td>
</tr>
</tbody>
</table>

   **Table 1 Recruitment condition of each species.**

   b) Mortality rate (Self-thinning functions)

   \[ \text{Trees}_{\text{sat}} = \frac{\text{Trees}_{\text{age}=0}}{\text{AGE}^{2}} \quad [\text{Eqn. 1}] \]

   \[ \text{Trees}_{\text{rob}} = \text{Trees}_{\text{age}=0} \times \left( \frac{\theta^{4}}{\theta^{4} + \text{AGE}^{4}} \right) \quad [\text{Eqn. 2}] \]

   \[ \text{Trees}_{\text{sp}} \] is the tree density of the respective species Salix, Robinia and Elaeagnus and \( \text{Tree}_{\text{age}=0} \) as the initial tree density.

   c) Canopy Density

   Assuming canopy area is circular, the canopy density is represented by:

   \[ \text{CanopyD} = \frac{\text{Leaf}}{\pi \left( \frac{C_{D}}{2} \right)^{2}} \times \text{Trees}_{\text{sp}} \quad [\text{Eqn. 3}] \]
ii. Hydrology sub-model component

Based on empirical data of the erosion depth and maximum inundation depth (Fig 2), a function to determine the erosion function was developed to be

$$Ed = k_{ed} \times Id$$  \hspace{1cm} \text{[Eqn. 4]}

whereby $Ed$ is Erosion depth, $k_{ed}$ is the erosion coefficient, 0.359 and $Id$ is the Inundation depth.

![Fig 2. The relation between erosion depth and inundation depth](image)

Also, the tree survival fraction function with respect to erosion depth and tree age (Fig 3) was developed to be

$$TrRatio = e^{-\frac{(Ed/k_{src})^2}{3} \times \left(\frac{AGE^2}{3^2 + AGE^2}\right)}$$  \hspace{1cm} \text{[Eqn. 5]}

whereby $TrRatio$ is the survival fraction, $Ed$ is erosion depth and $k_{src}$ is the survival rate coefficient of each tree species. In this model, $k_{src}$ of Salix is 0.745 and $k_{src}$ of Robinia is 0.475.

![Fig 3. The relationship between tree density survival fraction and inundation depth](image)

iii. Herb sub-model components

In this model, herbs are assumed to be recruited in spring (around April) and dies during winter (in December).

Table 2. Herb biomass equations and sky view factor

<table>
<thead>
<tr>
<th></th>
<th>Large grasses</th>
<th>Other plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNeffect (gDW/m²)</td>
<td>$AGB_c = 1500 \frac{TN^{2.5}}{0.04^{2.5} + TN^{2.5}}$</td>
<td>$AGB_o = 500 \frac{TN^{2.5}}{0.04^{2.5} + TN^{2.5}}$</td>
</tr>
<tr>
<td>Particle size (gDW/m²)</td>
<td>$AGB_c = 1500 \times 2.5^2 \times \frac{2.5^2 + (2 + log(D_{so}))^2}{2.5^2 + (2 + log(D_{so}))^2}$</td>
<td>$AGB_o = 500 \times 2.5^2 \times \frac{2.5^2 + (2 + log(D_{so}))^2}{2.5^2 + (2 + log(D_{so}))^2}$</td>
</tr>
<tr>
<td>Sky view factor</td>
<td>$SVF = 1 - 2\times(CanopyD)$</td>
<td></td>
</tr>
<tr>
<td>Shading effect</td>
<td>$AGB_c = AGB_c \times (SVF^{0.6})$</td>
<td>$AGB_o = AGB_o \times (SVF^{0.6})$</td>
</tr>
</tbody>
</table>

The biomass of large grasses increases with increasing total nitrogen, TN in the sediment and decreases with increase in particle size. Biomass of other herbs plants also follows the increasing trend with
TN concentration and the decreasing trend with increasing sediment size.

In addition, if canopy density (CanopyD) increases, the sky view factor decreases, low light penetration to the herbs, thus biomass decreases (Asaeda et al., 2012a).

iv. Nutrient cycle sub-model components

a. Percentage of TN concentration in each organ

Nitrogen are taken up by vegetation and allocated to each different organ shown in Table 3.

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Leaf</th>
<th>Stem</th>
<th>Root</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Salix</em> spp.</td>
<td>2.0</td>
<td>0.4</td>
<td>0.9</td>
</tr>
<tr>
<td><em>Robinia P.</em></td>
<td>3.0</td>
<td>0.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Herbs</td>
<td>0.4</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

*Table 3* Percentage of TN concentration in each organ

b. Nitrogen-fixing function

Some tree species are symbiotic to the nitrogen-fixing bacteria. Thus, the fraction of fixed nitrogen is also included in this model.

\[ Nfix = \exp \left( -1 \times \left( \frac{TN}{0.18} \right)^2 \right) \] [Eqn. 6]

\[ B_D(t) = B_0 \times (1 - \exp(-akt)) \] [Eqn. 7]

where \( B_D \): the decomposed amount, \( B_0 \) is the initial value, \( k \) is the decomposition rate coefficient (0.0024), \( t \) is duration time, \( a \) is a portion of carbohydrates and nutrient in the leaf (standard value: 0.3). In trees, \( \text{Leaf} (1-a) \) which is the biomass of the defoliated leaves on the ground is used and for herbs, the herb biomass is used.

d. Accumulated Soil TN

\[ TN_{day+1} = TN_{day} + Trbudget + Hbbudget + AtmN + FloodN \] [Eqn. 6]

\( TN_{day} \) is the accumulated Total Nitrogen for the current day, \( Trbudget \) is the trees TN budget, \( Hbbudget \) is the herbs TN budget, \( AtmN \) is atmospheric nitrogen (1g/m²) and \( FloodN \) is the N from flood.
(2) Study Area

Study was conducted on Arakawa Kumagaya River midstream sandbar [36°08'16"N; 139°20'32"E][1] for observed data. Dominant tree species found in Arakawa Kumagaya Area are *Salix* spp and *Robinia p.*

Elevation and particle size distribution input data was according to fieldwork observation [1].

*Fig. 5. Arakawa Kumagaya Area 0-15 sample points*

The hydrological data or flood history was obtained from MLIT, 2013. The highest flood was seen in September 2007 which inundated almost the whole sandbar.

*Fig 6. Water level data for Arakawa Kumagaya Area*

(3) Simulation process

For simulation, morphological and hydrological conditions settings are needed as the program’s input data. Elevation and particle size data of study area was obtained from fieldwork data whereas flood data was obtained from (Hydrology database, MLIT, Japan, 2013)

*Fig 7. Flowchart of the simulation process*
Assumption: Initial tree and herb density at the start of calculation is set to zero and initial TN is set to 100g/m$^2$. Climate, temperature or hydraulic factors are not considered.

3. Results

Note: 1. Yearly results were taken at the end of the simulated year (i.e. in December every year)
2. The before and after flood in the simulation are the results of one month before and after simulated flood of September 2007.

(1) Horizontal Tree distribution

Fig. 8. Observed [1] and simulated tree distribution before flood (BF) of 2007.

As can be seen from Fig 8 and 9, the distributions of Robinia and Salix for both observed and simulated have mutual agreement. The flood was in the 17th year of the calculation time.

Fig. 9. Observed [1] and simulated tree distribution after flood (AF) of 2007.

(2) Vegetation succession

Calculation started in 1991 whereby only few Salix species were recruited. Similarly, in 5th year of calculation, no Robinia was recruited but in the 10th year calculation, there was recruitment of Robinia. It was found that in August 1999, there was a 3.63m flood which had recruited Robinia. This vegetation succession continues until the last year of calculation.
Fig. 10. Tree distribution for 1st, 5th, 10th, 15th, 20th years of calculation

(3) Results according to sample points

Fig. 11. Observed and simulated comparison of herb biomass along the 16 points.

Fig. 12. Observed and simulated comparison of TN concentration along the 16 points.

(4) Horizontal herb biomass distribution

Fig. 13. Simulated herb biomass before (BF) and after (AF) 2007 flood.
After flood herb biomass distribution shown in Fig 13, it can be seen that the higher elevated areas retain their herb biomass and TN concentration.

4. Conclusion
Verification of the model by comparing the field observational data with simulated data, which had established an acceptable agreement, indicates that the model can be used to satisfactorily predict the vegetation succession, herb biomass and amount of nutrient present on a sandbar in a regulated river.

Discrepancies are believed to be due to other factors such as physical environment and hydraulic characteristics not being considered in this model.

5. Applications and further research
To apply this to other sandbars in another river, the morphological data and hydrological data of the desired sandbar is required.

The morphological condition (i.e. sandbar elevation) can be obtained more accurately by using Geographical Information System (GIS). The model may be improved by considering the hydraulic effects on the sandbar.

6. References


Year 2013 Master’s Thesis “A numerical approach on the modelling of nutrient dynamics and vegetation succession in midstream sediment bars of regulated river” ABU BAKAR Rabi’atul Adawiyah, Supervisor Professor ASAEDA Takashi