EXTENDING A HYDROMORPHODYNAMIC REDUCED COMPLEXITY MODEL WITH RIPARIAN VEGETATION DYNAMICS

EMILIO POLITTI
Department of Civil, Environmental and Mechanical Engineering University of Trento, Via Mesiano 77
Trento, 38123, Italy

WALTER BERTOLDI
Department of Civil, Environmental and Mechanical Engineering University of Trento, Via Mesiano 77
Trento, 38123, Italy

ALEX HENSHAW
School of Geography, Queen Mary University of London, Mile End Road
London, E1 4NS, UK

Hydraulic and morphodynamic numerical models have great importance in river management and restoration, as well as in flood protection planning. However, the computational demand of these types of models makes them unsuitable for long term predictions of landscape evolution. Such limitations led to the formulation of reduced complexity hydro-morphodynamic models that, to some extent, trade numerical accuracy for execution speed. Nevertheless, in both reduced complexity and classic numerical models, vegetation successional processes and their interactions with the physical habitat are poorly represented. This research proposes an extension of Caesar-Lisflood, a reduced complexity model that simulates flow and sediment transport in response to hydrological inputs. The riparian vegetation extension mimics woody species establishment, growth and dieback as well as their feedback on fluvial processes. Vegetation processes are modeled by means of two types of submodels: one based on fuzzy logic and the other based on “classical” equations. The hydromorphodynamic and vegetation model components are seamlessly coupled and spatially explicit. The model is grid based and operates on variable time steps to meet the different time scales at which physical and biological processes occur. The objective of this paper is to present the model concept and the preliminary results of 5 year simulation. The simulation was performed using parameters inferred from literature and expert knowledge. The results showed how the model is able to replicate vegetation changes in response to periods of low and high disturbance and generate a final landscape visually similar to the observed one.

1 INTRODUCTION

Hydrodynamic and sediment transport modeling has a relatively long tradition and many hydro-morphodynamic models are available in the research and industry domains. However, these types of models under represent the fundamental geomorphic role of vegetation. In more recent years within the scientific domain, many ecological models have been proposed to simulate changes in riparian vegetation in response to environmental and hydrological variables [1]–[6]. However, thus far, biological and physical riparian processes are modeled separately and full coupling of hydraulic, sediment transport and riparian vegetation models is still in its infancy [7], [8]. The hurdles to achieve such integration are related to technological challenges and knowledge gaps. Despite the rapid development of computational power, numerical modelling of hydro-morphodynamic processes is still computationally and, thus, time expensive. At the same time, the influence of physical processes on vegetation establishment, development and dieback are mostly known at qualitative levels and very few examples exist of widely applicable empirical laws that relate biological responses to physical habitat conditions.

Alternative approaches to hydro-morphodynamic modelling have lead to the formulation of reduced complexity hydro-morphodynamic models that, to some extent, trade numerical accuracy for execution speed. One example of this class of models is Caesar-Lisflood (CL) [9], a landscape evolution model that accounts for many physical processes occurring within active channels. Nevertheless, in CL, vegetation successional processes and their interactions with the physical habitat can be improved. This research presents a new riparian vegetation model that is fully integrated into the source code of CL and in order to mimic feedback between the physical and biological components of a simulated riparian system. The aim of this paper is to introduce the vegetation model concept and provide a first conceptual assessment of its functions.
2 METHOD

2.1 Caesar Lisflood

CL is a Landscape Evolution Model (LEM) created by the integration of LISFLOOD-FP [10] and CAESAR [11]. LISFLOOD-FP is a 1D model that applies a simplified form of the shallow water equations to route the flow along the x and y planar axis, thus simulating 2D flow. CAESAR is a LEM containing flow, erosion/deposition, lateral erosion, slope processes and vegetation submodels components. The CAESAR flow model computes an approximation of a steady state uniform, flow field. The integration of the two consisted of the replacement of CAESAR original flow model with LISFLOOD-FP [9], thus allowing a more realistic representation of hydrodynamics, including unsteady flows. CL operates on a regular grid (raster) data model, the physical variables simulated encompass: water depth, shear stress, flow velocity and direction, grain size spatial and vertical distribution and changes in topographic elevation (erosion/deposition). CL can operate in catchment or reach mode. The inputs are: an initial topography raster, a bedrock raster and a grain size distribution file (optional). Discharges are simulated using a rain-runoff model (catchment mode) or can be provided with an input file (reach mode). In both cases, the user can decide the time step of the inputs, i.e. the temporal resolution at which rain or discharge inputs are fed to CL.

2.2 Riparian vegetation model

2.2.1 Dealing with uncertainty of biological processes

Riparian vegetation spatial patterns and dependency to hydro-morphological processes have been largely described and studied (see [12] for an extensive review), however to describe such patterns and dependencies very few mathematical models have been proposed. Thus, the model presented here has been developed using a fuzzy logic approach, to take into account all those processes that cannot be represented with a suitable equation or whose mathematical implementation would result in computationally costly operations. Vegetation processes are modeled by means of two types of submodels: one based on fuzzy logic and the other based on “classical” equations.

2.2.2 Accounting for cumulative stress: fitness level factor

Riparian vegetation in natural or semi-natural contexts is exposed to a vast array of disturbances; however the effect of a single stress (e.g. a flood-event) on a plant might not lead to death but only reduce its health and strength. Cumulative stresses are accounted by keeping track of the fitness level of each vegetated cell. The fitness level factor ranges from 1 (maximum fitness) to 0 (extinction). The level decreases in response to mortality rates i.e. the percentage of individuals per cell deemed to die in response to the disturbance simulated by submodels. For example, if a cell has a fitness value of 0.8 and is affected by 50% mortality, the fitness of the cell will decrease by 50%, i.e. 0.4. Fitness level increases by 1/365 for each day in which no flood occurs, i.e. a cell with a critically low fitness level is assumed to fully recover its vigor if it is not flooded for almost one year.

2.2.3 Submodels

The model focus on woody riparian species and in order to properly represent and capture vegetation salient aspects, several vegetation attributes are stored in the model as 2D arrays (information layers). These layers are:

1. Age (years)
2. Stem Diameter at Breast Height (cm)
3. Height (cm)
4. Maximum root density depth (m)
5. Fitness level

Information layers 1-4 are provided as inputs in form of raster files. Riparian vegetation establishment, development and disturbance impacts are divided in several submodels that are computed independently and according to a set of rules explained in the section “Submodel timing and execution order”. Simulated landscapes are saved in form of raster grids once for every simulated year and before and after the occurrence of a flood.

Fuzzy recruitment

Seed recruitment inputs are: relative water elevation calculated as Euclidian distance of the topographic elevation from the mean water elevation of a recruitment month, and the substrate texture (e.g. coarse or fine). The result of the defuzzification is a “natality” rate i.e. the number of individuals per unit ground area (m²). Natality is then
transformed into individuals per cell by multiplying the natality by the cell size of the raster grid used in the modelling domain. The natality rate is also transformed into fitness index by computing the percentage of natality rate on the maximum of the possible natality rate. The recruitment submodel sets an initial height (H) of 50 cm and a diameter at breast height (DBH) of 3.5 mm for new individuals.

**Erosion**
This submodel will not have direct impacts on vegetation mortality but it reduces the depth of the maximum root density by an amount equal to the sediment eroded by CL, thus simulating the progressive roots exposition that triggers the Type II erosion process described in the “Shear stress” submodel.

**Fuzzy deposition**
Deposition causes individual mortality because of complete burial, mechanical damage and creation of anoxic conditions in the soil. In addition, the momentum generated by the motion of the sediments tends to bend the stems, thus further reducing individual plants height. Individuals’ sensitivity to small and moderate burial events is higher for young plants while, beyond a certain threshold, burial triggers anoxia that affects all age classes. The submodel is thus split into two components, the result of “deposition mortality” is a mortality rate percentage while the “deposition bending” effect is an angle of bending (degrees) which is used to calculate the new height (cm) of the plants in the cell.

**Fuzzy shear stress**
The shear stress submodel mimics plants dislodgement as a result of the pull out force exerted by floods [13]. Field observations and experiments proved that only individuals with shallow roots can be dislocated by the pull out effect, such condition is normally associated with young individuals. This mechanism is defined by [14]as uprooting mechanism of “Type I”. [14] recognize also a second uprooting mechanism, the “Type II” that occurs when, during floods, surface erosion gradually exposes plants’ roots until the anchorage provided by the unexposed roots is no longer sufficient to balance the drag exerted by the flow. The information layers for this submodel are therefore: root maximum density depth (e.g. shallow, medium and deep) and shear stress (e.g. low, moderate and strong).

**Fuzzy hydric stress**
The hydric stress submodel result is a mortality percentage and is evaluated by calculating the distance between the growing season mean water table of the current and previous year and the fitness level of the vegetation layer. The theory underpinning this submodel structure is a study from [15]. The study demonstrated that when the water table declines more than 1m, riparian woody species suffer from high mortality while declines less than 0.5m, only small effects on the growth performance are observed, furthermore [15] observed that mortality is higher for individuals with low vigor (i.e. low fitness).

**Roughness**
Roughness is assessed using a fuzzy approach. However, the resulting values of Manning's n do not have any effect on vegetation mortality but are instead used in the hydrodynamic computations of CL. The information layers used in this step are the stem density (number of individuals per cell), stem diameter (cm) and age (years). Stem density and stem diameter are used to assess the spacing of the individuals within a cell according to Equation 1:

\[
Sp = \sqrt{Sp^* (Sd/100)}
\]  

Where \(Sp\): Stem spacing, \(Sp^*\): Stem density \((\text{stems/m}^2)\) and \(Sd\): Stem diameter (cm). Manning’s n is thus assessed considering vegetation spacing and age, foliated (summer) and defoliated (winter) vegetation conditions are as well considered by defining two separate sets of fuzzy rules.

**Stem growth and Diameter at Breast Height**
Stem and diameter at breast height (DBH) growth is based on the equation of the Jabowa model [16]. The equation describes the ideal growth of individual trees and has several coefficients that must be fitted according to local species-specific characteristics such as maximum age (years), maximum diameter (cm) and maximum height (cm). The ideal growth is regulated by a coefficient ranging from 0 to 1. The coefficient depends on seasonal temperature, light availability and groundwater distance. In the presented model, Jabowa’s original coefficient is replaced by the fitness coefficient.
Root growth

Root growth is computed as the depth of the maximum root density as suggested by [17], thus setting the maximum root density depth (m) to 45% of the distance from the mean growing-season water table, for a maximum of 4m depth [18], [19].

2.2.4 Submodels timing and execution order

The seed-recruitment submodel is executed only during months of known seed dispersal and establishment of new seedlings is simulated at the end of each recruitment month. Erosion and deposition as well as shear stress are computed once each simulated time hour, when the inflow or the outflow is greater or equal to a given discharge deemed sufficiently high for causing substantial sediment mobilization (i.e. there is an ongoing flood). Growing submodels (stem, DBH and roots) are executed only once a year, at the end of the growing season. Roughness is computed each time there is a potential change in vegetation spatial, dimensional or ground per unit distribution, i.e. after recruitment, growth and disturbance submodels. A further control on roughness is the beginning and end of the leafy season which determines whether Manning’s’ n is estimated using winter or summer fuzzy set rules.

The vegetation model is coded in a separate library than CL but it makes use of the same data models and the execution is called from within CL routines. The two models are thus seamless integrated in a unique software package.

2.3 Case study

The proposed CL – riparian vegetation model has been tested on a reach of the Tagliamento River, (NE Italy) a free flowing braided river with bimodal hydrological regime [20]. The reach is located near the town of Pinzano (Figure 1), the length is approximately 1.5Km with a slope of approximately 0.003, the arboreal vegetation is dominated by *Populus Nigra L* [21], thus all the growth parameters have been set based on this species.

The simulated time spanned the years 2005-2009, the discharges fed to the model where measured on an hourly basis at the Pinzano gauging station. CL parameters were taken from [22] who applied Caesar to the Tagliamento while vegetation model parameters where gathered from literature or expert judgment.

Initial vegetation development stage and spatial arrangement was inferred by remote sensing data sources and previous studies [23]. A first assessment of the model’s logical consistency considered whether vegetation age classes’ quantitative distribution expressed as stage-area proportion over the all vegetated area, followed a pattern in accordance with the disturbance history defined by the input discharges. Vegetation age was selected as an overall indicator of vegetation dynamics. This information layer was saved at the end of each simulated-year growing season (set as 30th of October) and before and after the discharge at the inlet or outlet of the modelling domain reached or exceeded 100 m$^3$/s. The threshold was set after [22] and is the discharge at which significant sediment transport begins to occur in this section of the river [22]. Vegetation age classes were defined as “Initial”, “Transitional” and “Mature” stage according to [24], [25]. Additionally, the final year modeled map was visually assessed to evaluate whether the vegetation spatial patterns were realistic.

3 RESULTS

The simulation of the five years took approximately 10 days on a 8 Cores server mounting a Intel Xeon E5-2630 V3 2.40 GHz and equipped with a 16GB RAM.
Consistency between the simulated vegetation and the input flood history is displayed in Figure 2; the figure shows how the initial stage area declines even for the small flood events occurring at the end of 2005, this stage displays as well a very high variability, this is in accordance with studies that documented the extreme vitality and ease of recruitment of riparian pioneer species (e.g. Salicaceae) [26]. However, seed-recruited individuals exhibit low disturbance resistance, are exposed to frequent floods and thus have also a very high mortality rate [27]. Survived seedlings became transitional stage; the transition in Figure 2 is very evident and occurs at the end of each simulated year. This sudden change is the results of the growth submodel-execution which occurs at the end of the growing season. Transitional stage total area is steadily increasing during the simulation and has a sharp decline only with the large flood of October 2008. Mature stage total area remains quite stable over the whole simulation. There is a little increase only after the October 2008 flood. The reason of this increase, which might appear counter-intuitive, is again related the effect of the growth model. In the simulation, the flood begins the 28th of October and ends on the 1st, thus including also the instant in which the growth model is executed. The increase of Mature stage is thus the result of the net balance resulting from the loss of area due to disturbance and increase of area due to conversion of Transitional stage into Mature one.

![Figure 2 Hourly input discharges (y secondary axis) and vegetation stages simulated area (y primary axis).](image)

The simulation returns a landscape (Figure 3) with a plausible spatial pattern. The cumulative discharge on the right side of Figure 3 provides an estimate of the disturbance intensities of each simulated year. In 2005, the low disturbance allowed the formation of small Initial stages, later disrupted by several small floods at the end of 2006 (Figure 2). The year 2007 had an higher degree of disturbance than 2005, nevertheless, most of the Initial stage present in 2005 could proceed to the Transitional stage and few Initial stage patches were able to recruit (Figure 3), thus recovering from the later 2006 and early 2007 floods (Figure 2). The last year shown in Figure 3 is 2009: this year is characterized by a very high degree of disturbance; pioneer vegetation is almost absent (Figure 2 and Figure 3). It interesting to notice (Figure 3) that with the 2009 floods, also consistent areas of Transitional and Mature stage present on the island at the lower margin of the study site, are disrupted.

4 CONCLUSIONS

The presented research introduces several novel aspects; probably the most important one is the implementation of a fully integrated hydro-morphodynamic riparian vegetation model. The potential applications of such tool span from scientific research to river management and restoration decision support. The use of fuzzy logic allows application of the model also in cases where data are scarce, provided that a sufficient expert knowledge is available. Further element of novelty is the combination of Newtonian physics and fuzzy logic. Although this combination exist also in other riparian models (e.g.[28], [29]), the proposed model is able to simulate landscape evolution on a continuous temporal basis while the cited ones return a single snapshot of the considered riparian system.
The model assessment shows the behavior of the simulated vegetation is consistent with the hydrological inputs. Nevertheless, in this preliminary case study the definition of fuzzy sets and rules relied on extensive review of bibliographic information often not completely comparable to the conditions found at the Tagliamento and thus a refinement of the fuzzy sets based field observations is envisaged.

Further improvements are also possible at model conceptual level. Although the vegetation model attempts to include all the main drivers relevant for vegetation dynamics along a high energy gradient stream, it lacks for processes related to large wood dynamics. These types of processes are proved to be an essential landscape evolution driver [30] as they account for vegetation disruption through bank erosion and vegetation establishment trough re-sprouting of logs and wood fragments. Inclusion of such processes represents as well a future challenge that shall be addressed in order to provide a more realistic riparian landscape dynamics model.

REFERENCES


