Clement, Baptiste; Claude, Nicolas; Antoine, Germain; Duclercq, Marion

Development of a dynamic riparian vegetation model in TELEMAC-2D

Development of a dynamic riparian vegetation model in TELEMAC-2D

Baptiste Clement, Nicolas Claude, Germain Antoine & Marion Duclercq
EDF R&D National Laboratory for Hydraulics and Environment (LNHE)
Chatou, France
nicolas-n.claude@edf.fr

***Abstract*— Issues associated to the development of riparian vegetation in rivers become more and more considered by scientists and managers. Bio-hydro-morphodynamic numerical models can provide a significant help to better understand the complex interactions between plants and hydrogeomorphic processes, and can become helpful tools for streams management. It is in this context that a dynamic riparian vegetation model, based on the works of Van Oorschot *et al.* [2016] has been implemented in TELEMAC-2D. This model simulates colonization by seed dispersal, growth and mortality of plants of Salix type. Three mortalities were considered: uprooting, flooding and desiccation. The influence of vegetation on hydrodynamics is modelled by a drag force. The implementation of the ecological mechanisms has been tested and verified on a simple case. In the future, the present dynamic vegetation model can be improved by considering interactions between sedimentary processes and plants, by improving parameterization of ecological mechanisms and by modelling of multiple species.**

I. INTRODUCTION

Riparian vegetation is a common feature of rivers. In these hydrosystems, plants and hydrogeomorphic processes are strongly interconnected. Vegetation affect hydrodynamic by deflecting and reducing the flows [1], [2], [3], [4]. This influence is related to plants characteristics such as the density, stem diameter and height, and flexibility [5], [6], [7]. The impact of vegetation on flows also modifies the sediment transport. Thus, presence of plants tends to decrease sediment transport capacity, and causes deposition of particles [8], [9], [10]. The flow deflecting can also contribute to erode the bed close to patches [11], [12]. Furthermore, vegetation influences banks evolution by reinforcing soil cohesion thanks to the biomechanic action of roots and through addition of organic materials [13], [14]. Plants can also destabilize banks by modifying water circulation in the soil and causing mass failure [15]. At a larger scale, vegetation encourages the aggradation of alluvial bars [16] and secondary channels [17], and affects the river planform [18], [19].

In return, hydrology and morphodynamic processes affect also the vegetation dynamic. Riparian plants have adopted specific traits to survive to high disturbances encountered in streams, namely flooding, scour, burial and high flow velocities [20]. For example, riparian species use both sexual and asexual reproduction to optimize their recruitment in rivers, i.e. to colonize a maximum of wet and bare substrates [21]. In these systems, plants have also adapted their timing and period of seed dispersal to flow regime [22]. After germination, seedlings grow very fast in order to produce large dense roots systems to reduce the risks of uprooting [20]. The biomass development above riverbed is also very quick and leads to flexible stems to decrease their drag and their flow resistance [23].

Interactions between plants and hydrogeomorphic processes evolve with the age of vegetation [21]. During their early stage, plants have low effect on flow and sediment transport. However, during this phase, hydrogeomorphic disturbances strongly affect vegetation development. When plants get older, this relationship becomes more balance. Thereafter, with an adult population, the relationship is reversed and more unidirectionnal with plants affecting more the hydrogeomorphic processes than the opposite [16]. Thus, to simulate long-term evolution of a vegetated river, a model representing plants by only one age (without growth and mortality) seems not reliable [24]. For long-term morphodynamic prediction of rivers, it is necessary to take into account links between plants and hydrogeomophic processes, and to consider the evolution of these interactions as a function of the vegetation dynamic. Practically, this corresponds to couple a physic-based morphodynamic model to an ecological model which reproduces seed dispersal, colonization, growth and mortality of plants. Based on this assessment, [24] have recently proposed a sophisticated bio-morphodynamic model to study in details interactions between vegetation and morphodynamic of a meandering river.

The objective of our project is to couple a vegetation model to the TELEMAC-MASCARET system to provide in future an operational tool for river managers. To this end, a work was previously initiated to model the effect of vegetation on hydrodynamic [25]. This paper presents the second step which has consisted in implementing a dynamic riparian vegetation model based on the works of [24]. Note that a dynamic aquatic plant model was also implemented previously by [26]. The ecological model developed in this study simulates recruitment, colonization, growth and mortality of riparian plants. Thus, in a first part, we recall briefly how the effect of plants on hydrodynamic is modelled in TELEMAC-2D. In a second part, the dynamic ecological model is detailed. In a third part, the implementation of the ecological model is verified. Finally, a conclusion and some outlooks are proposed.

II. MODELLING THE EFFECT OF VEGETATION ON HYDRODYNAMIC

In this study, the hydrodynamic simulations were performed with TELEMAC-2D which solves the depth-averaged shallow-water equations with the finite element method. The effect of vegetation on flow is modelled by adding a drag force (*Fd*) in the momentum equations.

Drag force has been calculated from the following relation [7]:

$$\overrightarrow{F_d} = -\frac{1}{2} C_d \rho \alpha_v A * \min(h_v, h) * \left|\overrightarrow{U_v}\right| * \overrightarrow{U_v} \quad (1)$$

Where C_d is the drag coefficient, ρ is water density, α_v is a shape factor equals to 1 for a rigid cylinder, $A = m * D$ is the projected area of stems in the flow direction (with m the number of stems per m² and D the stems diameter), h_v and h are the plant height and the water depth, respectively, and $\overrightarrow{U_v}$ is the vector of flow velocity acting on the vegetation.

If $h_v \geq h$ (emerged vegetation), $\overrightarrow{U_v} = \vec{U}$, the depth averaged velocity. If not $h_v < h$ (submerged vegetation):

$$\overrightarrow{U_v} = \eta_v \vec{U} \left(\frac{h_v}{h}\right)^{1/2} \; with \; \eta_v = \frac{1 - D\sqrt{m}}{1 - \frac{h_v}{h} D\sqrt{m}} \quad (2)$$

Thus, to estimate the drag force induced by vegetation, the diameter, height and density of the considered plants should be known.

III. DESCRIPTION OF THE DYNAMIC RIPARIAN VEGETATION MODEL

A dynamic riparian vegetation model, based on the works of [24], has been implemented in TELEMAC-2D in order to simulate the establishment, the growth and the decay of plants in a river (Figure 1). The plants modelled have characteristics corresponding to Salix species.

Vegetation is defined in each node of the mesh by an occupation matrix:

$$Occ = \left(s_{i,j}\right)_{\substack{0 \leq i \leq a_{max} \\ 0 \leq j \leq t_{run}}} \quad (3)$$

Where $s_{i,j} \in [0,1]$ is the cover fraction related to the vegetation of age i during the year j of simulation. a_{max} is the maximum age of the plant (here *Salix* plants have a life expectancy of 60 years) and t_{run} the number of full years in the simulation. The initial vegetation cover is set up by defining the first column of the occupation matrix.

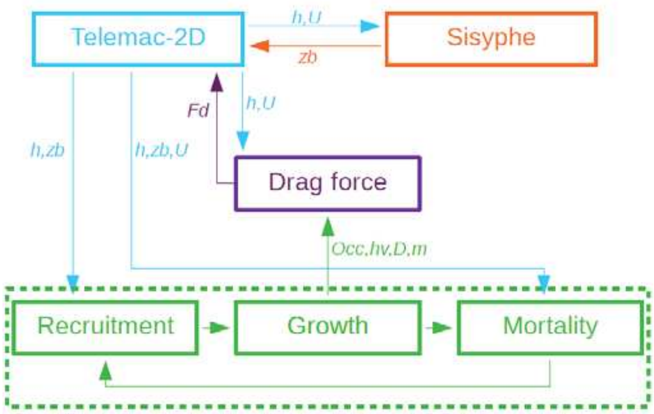

Figure 1. Diagram of coupling between TELEMAC-2D and the ecological model (shown by green dotted line).

A. *Evolution of the occupation*

Characteristics of vegetation (cover fraction, diameter, height, density) are updated once in a year after the window dispersal (see part III.B). The following equation gives the relationship between cover fraction of a vegetation at the year *j+1*, cover fraction at the year *j*, mortality at the year *j* ($\alpha_{i,j}$) and the initial fraction ($s_{i-j,0}$ or $s_{0,j-i}$):

$\forall \; i \; \geq 1:$

$$s_{i+1,j+1} = \max(s_{i,j} - \alpha_{i,j} * s_{i-j,0} \,;\, 0) \; si \; i \geq j \quad (4a)$$

$$or \; s_{i+1,j+1} = \max(s_{i,j} - \alpha_{i,j} * s_{0,j-i} \,;\, 0) \; si \; i < j \quad (4b)$$

At each (ecological) time step, the fraction of age *i+1* equals the fraction of age *i* a year before, minus the fraction freed by mortality. We distinguish the case where vegetation existed at the initial state ($i \geq j$), from the case where vegetation developed during simulation ($i < j$).

B. *Recruitment*

Riparian species have complex reproduction mechanisms adapted to hydrogeomorphic disturbances [20]. In the present model, we simplify these processes by only representing the sexual reproduction. The period of seed dispersal called window dispersal (WD) corresponds to the time when flow decreases in rivers (here it is supposed to be the month of June for *Salix* type). During this period, seeds are carried on by the river flow and the wind. Seeds germinate when they are deposited on a bare and wet substrate.

We assume that areas of germination at the year *j* are those submerged during WD ($h_{max}(t \in WD_j) > 0$) and emerged at the end of WD ($h\left(t = end\ of\ WD_j\right) = 0$). Thus, we are sure that seeds have been deposited on a wet substrate and that they have not been carried away by a water level rise.

When colonization takes place, the cover fraction of vegetation at age 0, $s_{o,j}$. is set up at 0.8 [24] when there is no plants at all. When plants occupy partially the bed, empty spaces are filled by a vegetation at age 0 [24]: $s_{o,j} = 1 - \sum_{i=1}^{a_{max}} s_{i,j}$.

C. Growth

Growth of plant height (h_v), root length (r), and stem diameter (D) were implemented as logarithmic functions (Figure 2) with the following formula [Van Oorschot et al. 2015]:

$$G = F_V * \log(i+1) \quad \forall i \geq 1 \qquad (5)$$

Where G is the size ($G = h_v \; ou \; r \; ou \; D$), F_V is the vegetation type dependent logarithmic growth factor and i is the vegetation age in years. The values of parameters are given in Table I.

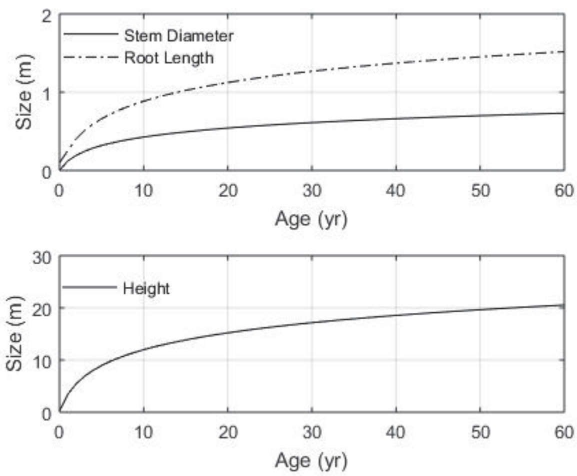

Figure 2. Growth curves of the *Salix* Type.

TABLE I. Vegetation growth parameter [24].

Parameters	Unit	Type	Reference
Vegetation type	-	*Salix*	
Maximum age	an	60	Braatne *et al.* (1996) [27]
Initial root length	m	0.1	Canadell *et al.* (1996) [28]
Initial shoot length	m	0.25	Van Velzen *et al.* (2003) [29]
Initial stem diameter	m	0.002	Van Velzen *et al.* (2003) [29]
Fv root	-	0.85	Canadell *et al.* (1996) [28]
Fv shoot	-	11.5	Kleyer *et al.* (2008) [30]
Fv diameter	-	0.41	Van Velzen *et al.* (2003) [29]
Timing of seed dispersal	month	June	Kleyer *et al.* (2008) [30]

D. Mortality

Plants start to die as soon as they are flooded or their roots are above the water table for 15 successive days or more [24]. Vegetation can also be uprooted from the substrate when the flow velocity is too high. The modelling of these processes is detailed in the following paragraphs. Plants can also die if they are buried by sediments or if a scour height gets higher than the length of roots. However, these two mechanisms are not yet implemented.

Total mortality of an age i at the year j of simulation, $\alpha_{i,j}$, corresponds to the sum of the mortality by flooding $a_{i,j}$, by desiccation $b_{i,j}$ and by uprooting $c_{i,j}$.

$$\alpha_{i,j} = \min(a_{i,j} + b_{i,j} + c_{i,j}, 1) \qquad (6)$$

The three mortalities are calculated using a threshold function Γ, applied to a variable called morphodynamic pressure related to the mortality considered [24]. The function is schematized below on the figure 3.

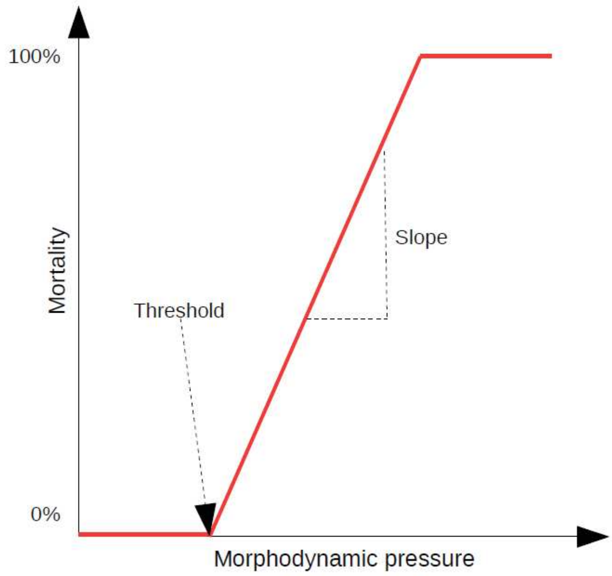

Figure 3. Form of mortality functions.

When the morphodynamic pressure overtakes a threshold value, mortality increases linearly until 100%. Function's parameters (threshold and slope) are characteristics of the mortality and the Life Stage (LS) of the vegetation considered. All values are displayed in Table II.

For mortality by flooding $a_{i,j}$, we compute $n_{sub,j}$ the number of days included in a period of 15 or more successive days of flood (days where water depth is not zero). Then $a_{i,j}$ is calculated by applying the appropriate Γ function:

$$a_{i,j} = \Gamma_{flood,LSk}(n_{sub,j}) \quad \forall i \geq 0, et \; i \in LSk \qquad (7)$$

Where *LSk* is the Life Stage in which belongs the age *i*.

TABLE II. Parameters of morality [24].

		Life stages *Salix* type				Reference
Parameter	**Unit**	**LS1**	**LS2**	**LS3**	**LS4**	
Number of years in LS	an	0	1-9	10-49	50-60	Van Velzen *et al.* (2003) [29]
Number of stems	stems/m²	25	15	0.16	0.16	Van Velzen *et al.* (2003) [29]
Desiccation threshold	days	25	190	240	365	Geerling *et al.* (2006) [31]
Desiccation slope	%/day	0.024	0.005	0.005	∞	Geerling *et al.* (2006) [31]
Flooding threshold	days	70	260	310	365	Geerling *et al.* (2006) [31]
Flooding slope	%/day	0.024	0.005	0.005	∞	Geerling *et al.* (2006) [31]
Flow velocity threshold	m/s	0.55	7.0	12.0	6.0	Geerling *et al.* (2006) [31]
Flow velocity slope	%/m.s^{-1}	2.4	0.5	0.5	0.5	Geerling *et al.* (2006) [31]

Likewise, mortality by desiccation $b_{i,j}$ is calculated by counting $n_{des,i,j}$, the number of drought day included in a period of drought longer than or equal to 15 days. A day is defined as dry when the roots do not reach the water table. We assume that the water table and the free surface have the same elevation i.e.:

$$z_b - r(i) > SL \tag{8}$$

Where z_b is the bed elevation, r is the root length and SL is the free surface elevation. Note that during drought conditions, there is no water in some areas covered by plants. To verify if roots reach the water table, we need to obtain a SL value on these dry nodes (see Eq. 8). For that purpose, we have partitioned the domain into several zones. In each zone, a reference point has been identified such as it is always under water. To verify if a non-submerged node is in dry condition or not (as defined above), we use the SL value calculated by TELEMAC-2D on its reference node.

Then $b_{i,j}$ is calculated as follows:

$$b_{i,j} = \Gamma_{desic,LSk}(n_{des,i,j}) \;\; \forall i \geq 0, i \in LSk \tag{9}$$

Mortality by uprooting $c_{i,j}$, is calculated by applying $U_{max,j}$, the highest flow velocity on the year j to the function Γ:

$$c_{i,j} = \Gamma_{uprooting,LSk}(U_{max,j}) \;\; \forall i \geq 0, i \in LSk \tag{10}$$

IV. Validation of Implementations

In this part, we present the results of a simulation carried out to check that the processes and equations presented above were correctly implemented into TELEMAC-2D.

A. Presentation of the model

The model represents a straight rectangular canal of 76.5 m long and 1 m large. The bathymetry, inspired from the experiments of [32], has been defined in order to have a bed slope of 0.05% with a low part (channel) and high part (bar) (Figure 4). The mesh is composed of more than 32000 nodes, spaced in average of 5 cm. Boundary conditions are a water discharge at the inlet and free surface elevation at the outlet of the channel.

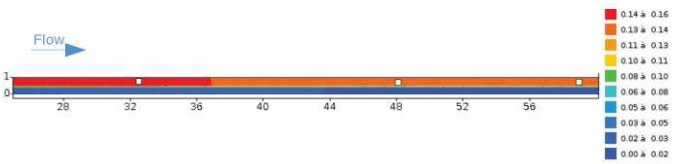

Figure 4. Bed elevation (m) in the model. From left to right, the 3 white squares indicate nodes n°15896, n°21803 and n°25928.

B. Hydrograph

A simplified hydrograph has been imposed at the inlet boundary to test the processes implemented in the ecological model (Figure 5 and Table III). The hydrograph is composed of four discharges: one flow to submerge the bar (Q = 0.04 m^3/s), one flow with an emerged bar (Q = 0.02 m^3/s), one flow corresponding to a drought situation, when roots do not reach the free surface (Q = 0.015 m^3/s) and one flow to reach high velocities in order to uproot young vegetation from the bar (Q = 0.1 m^3/s). Roots length has been fixed to 2 cm for all the life stages to simplify the test. Five years were simulated to observe the vegetation evolve 5 times. The implementation of an ecological process is tested each year of the simulation (Table III). To reduce computation time, 3 seconds in the model represent a day in real life.

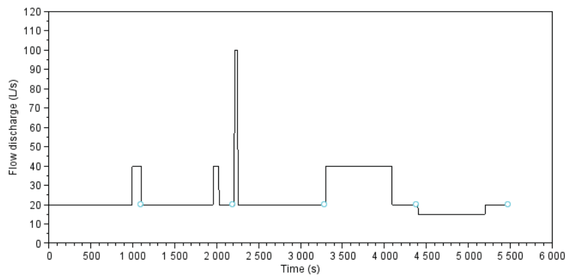

Figure 5. Hydrograph used for the test. Transitions between each ecological time steps (each years) are marked by blue circles.

TABLE III. Test program.

Year	Date of the end of year (s)	Processes tested
1	1095	Recruitment failure
2	2190	Recruitment
3	3285	Uprooting
4	4380	Flooding
5	5475	Desiccation

C. *Validation of the processes implementation in the ecological model*

Figure 6 shows the cover fractions of vegetation that germinates on the bar (0 years old - LS1) for each year of the simulation. Figure 7 presents each year the sum of cover fractions of vegetation that are 1 to 9 years old (LS2)

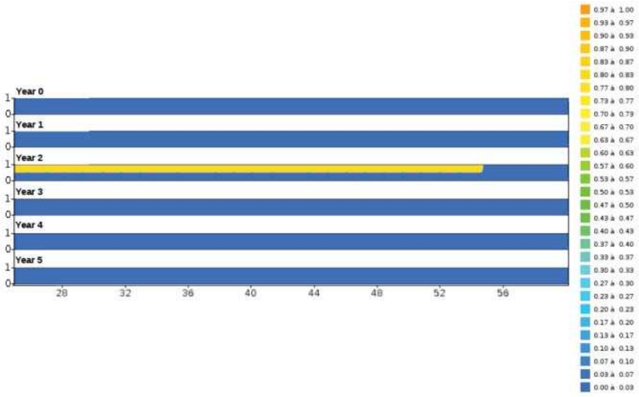

Figure 6. Cover fraction for the LS1.

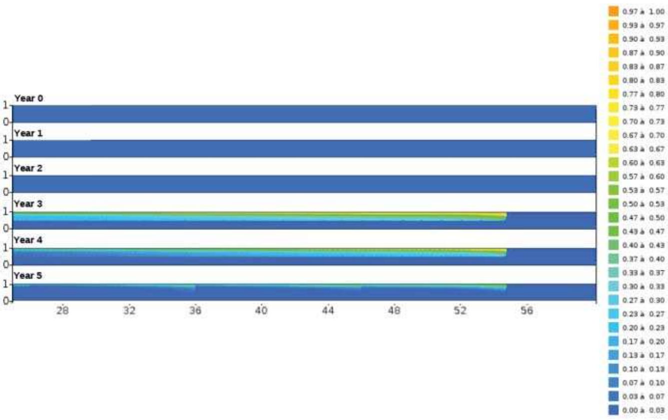

Figure 7. Cover fraction for the LS2.

1) *Year 1: Recruitment failure*

There is no vegetation at initial state (year 0 in Figures 6 and 7). The hydrograph of the first year is composed of a flood that starts during the window dispersal (WD) and finishes after this period. So, the bar is still submerged on the 1st of July at the end of the WD (Figure 8). As no bare and wet substrate is available to allow a plant recruitment, no vegetation appears during year 1 (LS1 is empty, see Figure 6).

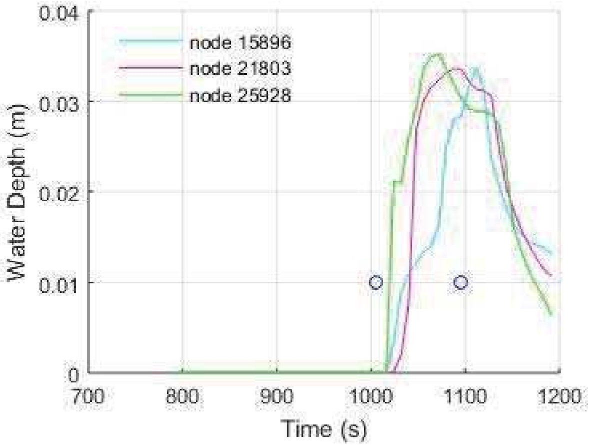

Figure 8. Water depth on 3 nodes located on the bar at the end of year 1. Blue circles mark the beginning and the end of the window dispersal. See Figure 4 for the location of the 3 nodes.

2) *Year 2: Recruitment*

During the second year of the simulation, a flood begins before the window dispersal and finishes before the 1st of July. With this hydrology, a large part of the bar becomes emerged during the WD (see nodes 15896 and 21803 on Figure 9) and then is colonized by plants (Figure 6, year 2). The cover fraction related to new vegetation is 0.8. We also see in the downstream part of the bar that plants do not colonize the substrates which are not submerged during the WD (see node 25928 on Figure 9, and Figure 6).

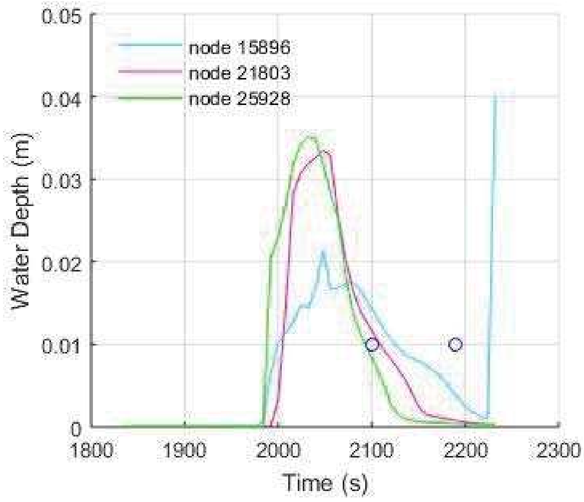

Figure 9. Water depth on 3 nodes located on the bar at the end of year 2. Blue circles mark the beginning and the end of the WD. See Figure 4 for the location of the 3 nodes.

3) *Year 3: Uprooting*

Vegetation established at the end of the second year is now 1 year old (LS2, Figure 7). The third year of simulation is marked by a large flood with maximal velocities (U_{max}) sufficiently high on the bar (Figure 10) to allow locally the uprooting of some plants (i.e. U_{max} higher than 0.55m/s, see Table II). This explains why the spatial distribution of the cover fraction of LS2 is similar to the spatial distribution of U_{max}.

To check the calculation of mortality by uprooting, a comparison of the results of the simulation on one node with a handmade calculation using equations given part III is performed. For that purpose, node n°21803 is considered. TELEMAC graphic outputs give 0.79 m/s, a fraction of 0.8 at year 2 and a fraction of 0.33 at year 3. According to Figure 3 and Table II, mortality by uprooting reaches a value of 2.4*(0.79-0.55) = 0.58. We find the same occupation at the year 3 than the implemented model since thanks to Eq 4: 0.8-0.58*0.8 = 0.33.

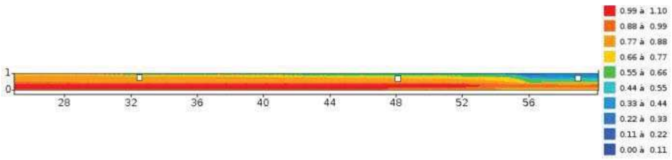

Figure 10. U_{max} (m/s) during year 3. From left to right, the 3 white squares indicate nodes n°15896, n°21803 and n°25928.

4) Year 4: Flooding

During the year 4, a very long flood has been simulated. The bar is flooded almost uniformly more than 260 days (Figure 11), which overcomes the mortality threshold by flooding for LS2 (Table II). It leads to a slight decrease of the cover fraction of vegetation on the bar (Figure 7, year 4).

To verify the calculation performed by the code, we use the node n°21803 which has been flooded 283 days (Figure 11) and presents a new fraction of 0.24 at year 4 (Figure 7). According to Figure 3 and Table II the mortality by flooding is estimated manually to 0.005*(283-260) = 0.115. Then, the new fraction is deduced: 0.33-0.8*0.115 = 0.23. The result of the handmade calculation is equal to the result of the simulation.

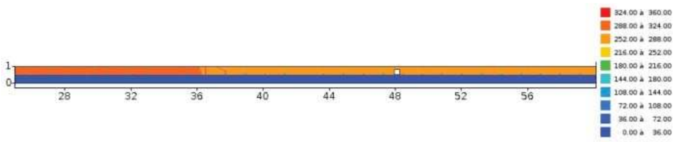

Figure 11. . Number of flooded days (N_{sub}) during year 4. Node n°21803 is indicated by a white square.

5) Year 5: Drought

The fifth year of simulation presents a long period of low flow. For these flow conditions, the roots are not connected to the water table. The dry period is longer than the mortality threshold by drought for LS2 (Table II). Thus, a part of the plants dies by desiccation during this year (Figure 7, year 5). At the end, vegetation is still present close to the left bank and across the bar with a regular spacing (Figure 7). This spatial distribution is partly due to the domain partitioning method used to estimate the water table elevation (part III.D). The method to reproduce vegetation mortality by desiccation will be improved in the future.

To check the calculation, we perform a handmade calculation of the mortality by drought on the node n°21803. This area has been in drought conditions 258 days during year 5 (Figure 12). At the end of this year, the fraction is null on the node. According to Figure 3 and Table II the mortality by drought can be estimated to 0.005*(258-190) = 0.34. The new fraction is then 0.23-0.8*0.34 < 0. Since a fraction cannot be negative, the result is rounded to 0. Thus, the handmade calculation and the simulation give the same result.

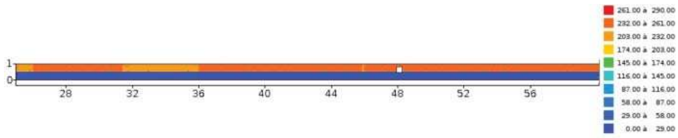

Figure 12. Number of drought days (N_{des}) during year 5. Node n°21803 is indicated by a white square.

V. CONCLUSIONS AND OUTLOOKS

Issues associated to the development of riparian vegetation in rivers become more and more considered by scientists and managers. Bio-hydro-morphodynamic numerical models can provide a significant help to better understand the complex interactions between plants and hydrogeomorphic processes, and can become helpful tools for streams management.

A dynamic riparian vegetation model, based on the works of [24] has been implemented in TELEMAC-2D. This model simulates colonization by seed dispersal, growth and mortality of plants of Salix type. Three mortalities were considered: uprooting, flooding and desiccation. The implementation of these mechanisms has been tested and verified on a simple case.

This work constitutes a first step toward a more complete and realistic bio-hydro-morphodynamic model. Several outlooks can be listed, among others:

- To model interactions between vegetation and sedimentary processes since these relationships control significantly the evolution of rivers [16]. A preliminary work would consist in modelling the plants death by burial and scour.
- To optimize the parameterization of ecological processes (growth and mortality curves) by calibrating the parameters from field or laboratory measurements.
- To complete the model in order to simulate the dynamic of multiple species (poplars, invasive or protected species…), their interactions and the feedbacks of plant communities on the flow and sediment transport.

Furthermore, a first application is ongoing on a 3 km long reach of the Isère River (Figure 13). The objective is to better understand the effect of flow regulation on plants development. For this purpose, a TELEMAC-2D model is coupled to the ecological model described in this paper and two hydrographs are simulated: one corresponding to natural flows and one representing regulated flows. For instance, Figure 14 shows, as preliminary result, the evolution of the recruitment areas during 3 years for a regulated hydrology. Thereafter, a comparison of the 2 simulations will be carried out to characterize qualitatively the influence of the water management on vegetation dynamic.

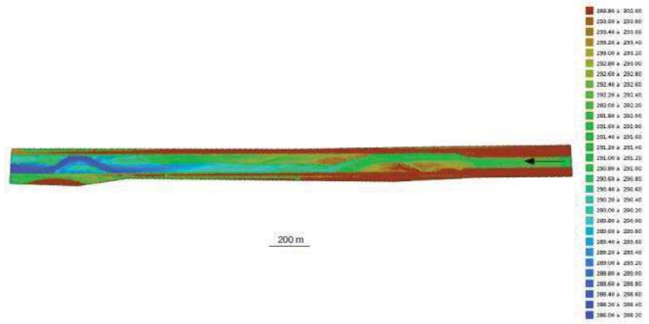

Figure 13. Bathymetry of the study reach represented in the TELEMAC-2D model. The black arrow indicates the flow direction.

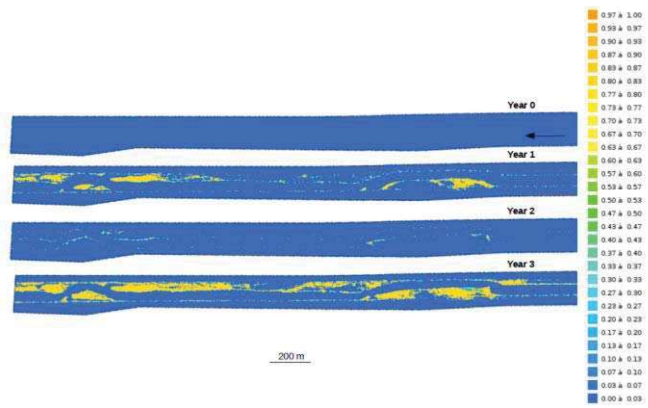

Figure 14. Fraction of area colonized by seedlings.

REFERENCES

[1] W. L. Cowan, "Estimating hydraulic roughness coefficients", Agricultural Engineering, 37(7), 473-475, 1956.

[2] D. Liu, P. Diplas, J. Fairbanks, and C. Hodges, "An experimental study of flow through rigid vegetation", *Journal of Geophysical Research: Earth Surface*, 113(F4), 2008.

[3] L. Zong, and H. Nepf, "Spatial distribution of deposition within a patch of vegetation", *Water Resources Research*, 47(3), 2011.

[4] H. Nepf, "Hydrodynamics of vegetated channels", *Journal of Hydraulic Research*, 50(3), 262-279, 2012.

[5] S. Petryk and G. Bosmajian, Analysis of flow through vegetation, *Journal of the Hydraulics Division*, *101*(7), 871-884, 1975.

[6] M. Baptist, V. Babovic, J. Rodríguez Uthurburu, M. Keijzer, R. Uittenbogaard, A. Mynett and A. Verwey, "On inducing equations for vegetation resistance", *Journal of Hydraulic Research*, *45*(4), 435-450, 2007.

[7] W. Wu, F. D. Shields, S. J. Bennett and S. S. Wang, "A depth-averaged two-dimensional model for flow, sediment transport, and bed topography in curved channels with riparian vegetation", *Water Resources Research*, *41*(3), 2005.

[8] F. López and M. García, "Open-channel flow through simulated vegetation: Suspended sediment transport modeling", *Water resources research*, *34*(9), 2341-2352, 1998.

[9] T. Tsujimoto, "Fluvial processes in streams with vegetation", *Journal of hydraulic research*, *37*(6), 789-803, 1999.

[10] E. M. Follett and H. M. Nepf, "Sediment patterns near a model patch of reedy emergent vegetation", *Geomorphology*, *179*, 141-151, 2012.

[11] T. Bouma,, L. Van Duren, S. Temmerman, T. Claverie, A. Blanco-Garcia, T. Ysebaert and P. Herman, "Spatial flow and sedimentation patterns within patches of epibenthic structures: Combining field, flume and modelling experiments", *Continental Shelf Research*, *27*(8), 1020-1045, 2007.

[12] S. Temmerman, T. Bouma, J. Van de Koppel, D. Van der Wal, M. De Vries and P. Herman, "Vegetation causes channel erosion in a tidal landscape", *Geology*, *35*(7), 631-634, 2007.

[13] M. J. Van de Wiel and S. E. Darby, "A new model to analyse the impact of woody riparian vegetation on the geotechnical stability of riverbanks", *Earth Surface Processes and Landforms*, *32*(14), 2185-2198, 2007.

[14] N. Pollen-Bankhead and A. Simon, "Enhanced application of root-reinforcement algorithms for bank-stability modeling", *Earth Surface Processes and Landforms*, *34*(4), 471-480, 2009.

[15] M. Rinaldi and N. Casagli, "Stability of streambanks formed in partially saturated soils and effects of negative pore water pressures: the Sieve River (Italy)", 1999.

[16] A. Gurnell, "Plants as river system engineers", *Earth Surface Processes and Landforms*, *39*(1), 4-25, 2014.

[17] S. Rodrigues, J.-G. Bréhéret, J. J. Macaire, S. Greulich and M. Villar, "In channel woody vegetation controls on sedimentary processes and the sedimentary record within alluvial environments: a modern example of an anabranch of the River Loire, France", *Sedimentology*, *54*(1), 223-242, doi:10.1111/j.1365-3091.2006.00832.x, 2007.

[18] M. Tal and C. Paola, "Effects of vegetation on channel morphodynamics: results and insights from laboratory experiments", *Earth Surface Processes and Landforms*, *35*(9), 1014-1028, 2010.

[19] W. M. Van Dijk, R. Teske, W. I. van de Lageweg and M. G. Kleinhans, "Effects of vegetation distribution on experimental river channel dynamics", *Water Resources Research*, 49(11), 7558-7574, 2013.

[20] S. Karrenberg, P. J. Edwards and J. Kollmann, "The life history of Salicaceae living in the active zone of floodplains", *Freshwater Biology*, *47*(4), 733-748, 2002.

[21] D. Corenblit, E. Tabacchi, J. Steiger and A. M. Gurnell, "Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches", *Earth-Science Reviews*, *84*(1), 56-86, 2007.

[22] J. M. Mahoney and S. B. Rood, "Streamflow requirements for cottonwood seedling recruitment-an integrative model", *Wetlands*, *18*(4), 634-645, 1998.

[23] F. Siniscalchi and V. Nikora, "Dynamic reconfiguration of aquatic plants and its interrelations with upstream turbulence and drag forces", *Journal of Hydraulic Research*, *51*(1), 46-55, 2013.

[24] M. van Oorschot, M. G. Kleinhans and H. Middelkoop, "Distinct patterns of interaction between vegetation and morphodynamics", *Earth Surface Processes and Landforms*, 2016.

[25] N. Claude, G. Antoine, R. Yassine, V. Verschoren, C. Schwarz, S. Temmerman and C. Jourdain, "Numerical simulations of flow around vegetation with TELEMAC-2D: application on laboratory xperiments and on the Isere river (France)", *Proceeding of XXII TELEMAC-MASCARET User Conference*, Daresbury (UK), October, 2015.

[26] V. Verschoren, C. Schwarz, J. Schoelynck, K. Buis, G. Antoine, N. Claude, P. Meire and S. Temmerman, "Implementing plant growth of flexibele aquatic", *Proceeding of XXII TELEMAC-MASCARET User Conference*, Daresbury (UK), October, 2015.

[27] vegetation into a hydrodynamic model (Telemac2D)

[28] J. Braatne, S. Rood and P. Heilman, "Life history, ecology and conservation of riparian cottonwoods in north America". In: Stettler, R., Bradshaw, G., Heilman, P., Hinckley, T. (Eds.), Life history, ecology, and conservation of riparian cottonwoods in North America. NRC Research Press, Ottawa, Ch. 3, pp. 57–85, 1996.

[29] J. Canadell, R. B. Jackson, J. B. Ehleringer, H. A. Mooney, O.E. Sala and E.D. Schulze, "Maximum rooting depth of vegetation types at the global scale". *Ecologia* 108 (4), 583–595, 1996.

[30] E. Van Velzen, P. Jesse, P. Cornelissen and H. Coops. "Stromingsweerstand vegetatie in uiterwaarden. Deel 2 achtergronddocument versie 1" (Dutch). Tech. rep., RIZ, Arnhem, 2003.

[31] M. Kleyer, Bekker, R., Knevel, I., Bakker, J., Thompson, K., Sonnenschein, M., Poschlod, P., van Groenendael, J., Klimes, L., Klimesova, J., Klotz, S., Rusch, G., Hermy, M., Adriaens, D., Boedeltje,

G., Bossuyt, B., Dannemann, A., Endels, P., Götzenberger, L., Hodgson, J., Jackel, A.-K., Kühn, I., Kunzmann, D., Ozinga, W., Römermann, C., Stadler, M., Schlegelmilch, J., Steendam, H., Tackenberg, O., Wilmann, B., Cornelissen, J., Eriksson, O., Garnier, E., Peco, B, "The LEDA Traitbase: a database of life-history traits of the Northwest European flora", *Journal of Ecology* 96 (6), 1266–1274, 2008.

[32] G. Geerling, A. Ragas, R. Leuven, J. van Den Berg, M. Breedveld, D. Liefhebber and A. Smits, "Succession and rejuvenation in floodplains along the river Allier (France)". *Hydrobiologia* 565 (1), 71–86, 2006.

[33] E. Pasche and G. Rouve, "Overbank flow with vegetatively roughened flood plains", *Journal of Hydraulic Engineering*, *111*(9), 1262-1278, 1985.