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HYDRAULIC MANAGEMENT OF FILAMENTOUS ALGAE IN OPEN-CHANNEL NETWORKS: CASE STUDY IN SOUTHERN FRANCE

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Periphyton constitutes the benthic compartment of aquatic environments such as artificial channels which are specific eco-systems for many reasons. Firstly, they have to fulfill hydraulic performance and water quality objectives. These objectives may be affected by filling problems due to algal developments and sanitary risks linked to toxins secreted by Cyanobacteria. Second, compared to natural streams, artificial channels have a relatively simple geometry and their hydraulic variables are easier to monitor. Also, cross regulators allow the managers to control discharges and water elevations.

Periphyton dynamics depend on several factors and hydrodynamic is one of the most crucial one. In this article we analyze an original strategy for algal control currently used in a branch of the Canal de Provence (South of France). The management strategy consists of regular flushes causing increases of the bed shear stress from upstream to downstream and consequently algal filament cutting. This is achieved by increasing the discharge at the upstream end of the branch.

We first show that turbidity can be used as an indicator for algal detachment. Then, a detachment model is proposed and coupled with the hydrodynamic simulation of the system. It can be fitted very satisfactorily on the turbidity measurements and can be used to improve the management strategy, such as reducing the discharge released.

Keywords: filamentous periphyton, irrigation canal, hydrodynamics, shear stress, eco-hydraulics, open-channel flow

INTRODUCTION

Numerical models have become very efficient in simulating the hydraulic behavior of open-channel networks, and are widely used nowadays for canal design and even canal management [4, 13]. Yet, channel modelers are challenged by other issues with a growing importance for canal managers, such as vegetation development that may affect the hydraulic conveyance of the network. As a part of it, periphyton (fixed algal communities) can grow rather quickly on canal banks and have a strong impact on water distribution. Periphyton is generally composed of a lot of species. Some of them are forming filamentous colonies up to several meters long, while other species grow in biofilms. The first kind of nuisances is due to filament detachment. This detachment can produce drift of big clusters or fragment the filaments in thin particles. Both are source of clogging problems. The clusters are stopped by the hydraulic devices (gates, pipes, weirs, measuring devices) and thin fragments of filaments can fill filters very quickly. These constraints require numerous mechanical interventions to avoid overflows. Moreover, drifting algae cells increase water turbidity and organic matter, increasing treatment costs. Another constraint is the sanitary risk linked to the particular species of Cyanobacteria likely to produce toxic substances. Even if the observed concentrations are very low and do not present a risk according to World Health Organization’s recommendations in a lot of irrigation networks, an effort is made to prevent these algae development.

The present paper analyzes management strategies of periphyton, based on hydraulic control. The studied system is the Canal de Provence, which supplies 79 769 ha of irrigated land in the South of France, several industries and large drinking water plants. Hence, water quality is a major issue, and chemical treatments cannot be used. An original strategy consists in flushing algal developments every two weeks on a pilot site.

The purpose of this study is to analyze the current strategy in order to understand and quantify the processes involved, then to apply it to other sites. To this end, the flushes are simulated with a hydrodynamic model coupled with a new detachment model. The simulated detachment is finally compared with turbidity measurements.

PRESENTATION OF THE CASE STUDY

The studied system is the Branch of Marseille Nord (BMN) in the Canal de Provence (Southern France). The BMN supplies 30 % of the water requirements of the city of Marseille. The branch starts at the Bimont Dam fed by water coming from the Verdon river and ends at the Vallon Dol tank, 31.5 km downstream; the canal is a lined, trapezoidal and open-channel, except in 10.9 km of galleries. The downstream discharge capacity is 3.5 m^3/s. 50% of the volume is transferred to the downstream end, the other part is withdrawn along the branch. The BMN hydraulic management uses dynamic and automatic regulation. Compared to traditional irrigation networks, production of drinking water imposes extra constraints regarding hydraulic management (continuous supply, demand-based delivery) and water quality. Algal development is present throughout the year; it affects the hydraulic performance by obstructing distribution and metering systems, and threatens the water quality by increasing turbidity (maximum acceptable value of turbidity is around 20 NTU) and “éventuels” sanitary risks. The canal network is equipped with continuous monitoring systems for hydraulic variables (discharges, water level and weirs position) and some quality parameters (turbidity, temperature). All data are stored at a 15 minutes time step. There are four monitoring stations named Bimont, G5, G7 and Vallon Dol located respectively at 0 m, 19096 m, 22566 m and 31436 m from the upstream end.

An empirical study has been carried out in 2004 [11] to evaluate possibilities of algae control by hydraulic operations. Three different discharge increases (0.7, 1 and 1.3 m^3/s) were tested and compared in terms of biomass detachment, biological nuisances (sanitary risk) and physical nuisances (turbidity increase). It resulted in the strategy currently applied to the BMN: every three or two weeks, the discharge is increased by 1 m^3/s during 6 hours, whatever the initial discharge value (1 to 1.5 m^3/s). The principle is to cut algal filaments before they are too long in order to limit the periphytic biomass and to control its detachment. The excessive water inflow is stored in the Vallon Dol tank, and therefore is not lost in compliance with the Canal de Provence objective of water resource preservation. Since this strategy is efficient to control algal development, the canal managers intend to apply it to other branches. This management principle should also be adapted for the BMN if the canal operation is modified, for instance due to an increase in water demand. The difficulty is to design the hydraulic operations that should be applied, to avoid heavy maintenance operations, to estimate the efficiency of the method and the risk to get too highly turbid waters. Water release should also be limited if it cannot be stored. Hydrodynamic models can be efficient tools to design such operations. In the following, we present the model used to analyze the flushes carried out on the BMN. The application to other systems is discussed further.

MODELING APPROACH

Hydrodynamics variables

The hydrodynamic behavior of the studied canal is simulated with SIC (“Simulation of irrigation Canals”), a commercial software dedicated to open-channel irrigation networks management [4]. The flow is determined by resolution of the one-dimensional Saint-Venant’s equations using the implicit Preissmann scheme. The friction losses are calculated by the Manning roughness formula. Cross structures (gates, weirs) and delivery points (pipes, gates, weirs) are modeled using appropriate discharge equations. The computation space step is around 200 meters and the time step is set to 5 minutes. Thanks to a data import option, boundary conditions are read from the Canal de Provence database.

The simulations outputs are the discharge and the water levels at each calculation time step and each calculation section. From these two variables and the physical characteristics, it is possible to calculate all the one-dimensional hydraulic variables, such as mean velocity or the mean bottom shear stress:

$$\tau_0 = \rho\, g \frac{n^2 U^2}{R_h^{\ 1/3}} \tag{1}$$

Where τ_0 is the mean bottom shear stress (N/m^2), ρ the water density (kg/m^3), g the acceleration due to gravity (m/s^2), R_h the hydraulic radius (m), U the mean velocity (m/s) and n the Manning roughness coefficient (s/m$^{1/3}$). This shear stress is obtained by writing the equilibrium of a water column of the flow, on which the applied forces are its weight, the pressure forces and the resistance of the substratum. This bottom shear stress is often used as a key variable in bed erosion processes [18].

Detachment process

In this study, the evolution of periphyton (fixed algae) and drift algae (transported algae) are considered. While conducting flush operations, algal filaments are cut and transported downstream. The convection-dispersion process for an element is expressed as follows:

$$\frac{\partial AC}{\partial t} + \frac{\partial (QC)}{\partial x} = \frac{\partial}{\partial x}\left(DA \frac{\partial C}{\partial x} \right) + E(x,t)A \tag{2}$$

In which A is the wetted area (m^2), C is the concentration of the transported element (kg/m^3), Q is the discharge (m^3/s), D the diffusion-dispersion coefficient (m^2/s) and E is the exchange term with the substratum (kg.m^{-1}s^{-1}). The periphyton biomass evolution $B(x,t)$ depends on its growth and on the detachment process expressed by the exchange term E. During a flush, the algal growth is insignificant so the evolution of B is obtained by the following conservation equation:

$$\frac{dB}{dt} = -E \tag{3}$$

Where B is the fixed biomass of periphyton (kg/m) on the canal banks. The initial condition is denoted $B_0(x)$.

A difficult task is to evaluate the exchange term E, which, unlike for sediment erosion processes, has been little studied in the past. Detachment models are of two types. A few models are based on mechanical effects exerted at the filament scale [14, 2, 1]. The drag force is expressed as a function of the local flow characteristics, the filament length and diameter. Detachment can occur if a critical shear stress is reached, depending on the biological properties of the algae. One can point out that local velocities are difficult to predict, that periphyton cannot be considered as a homogeneous medium, and that detachment (and the resulting increase of turbidity) is also linked to other processes, such as near bed transport. This is why more integrative approaches have been developed, linking the global flux of biomass to hydraulic variables such as the velocity [19, 16, 15], or the discharge [10, 17]. This kind of approach is more appropriate at the canal scale and is adopted here. Following a classical assumption done for sediment transport, we assume that the effective detachment capacity is linked to the mean bottom shear stress τ_0:

$$E=\alpha\left(\frac{\tau_0-\tau_{0,cr}}{\tau_{0,ref}}\right)^{\beta}B \tag{4}$$

Where E is the detached biomass per unit of time, α is a non-dimensional detachment coefficient expressing the algal sensitivity to the physical stress, subscript *cr* stands for critical and *ref* for reference. Setting $\tau_{0,ref}= \tau_{0,cr}$ implies that detachment depends on the relative rather than the absolute increase of shear stress. Previous studies [6, 7, 8, 12, 9] identified the existence of a threshold for algal detachment. This threshold depends on the conditions in which the algae have grown, which is possible due to species adaptation. In our case, one can suggest that the critical shear stress is close to the one applied during the growth period.

ANALYSIS OF A PERTURBATION

Using turbidity as a detachment indicator

Let us assume that the discharge increase produces a stress on algal filaments higher than the critical value of resistance. The filaments are cut so that they are resuspended in the water column. The water turbidity is linked to the quantity of suspended particles which are mineral and organic, and to the particles diameter. The link between drift biomass concentration and turbidity was studied by Galindo [11]. These data provide a very good linear fitting between both quantities (Figure 1). We can conclude that turbidity can be used as a good indicator of algal detachment during flushes, and then the detached biomass can be quantified.

Shear stress evolution during a flush

Several flushes were simulated using SIC model. Results of the shear stress dynamic during the perturbation of the 24 May 2007 are displayed in Figure 2 for two stations. The turbidity increase appears after the shear stress increase with a lag-time due to convection in the canal (distance of about 3.5 km). The second increase of shear stress has very little effect on turbidity: we can assume a depletion phenomenon in the periphyton stock, which means that the operation has been efficient and can be stopped.

In order to simulate alternative operations, both detachment and depletion processes must be simulated.

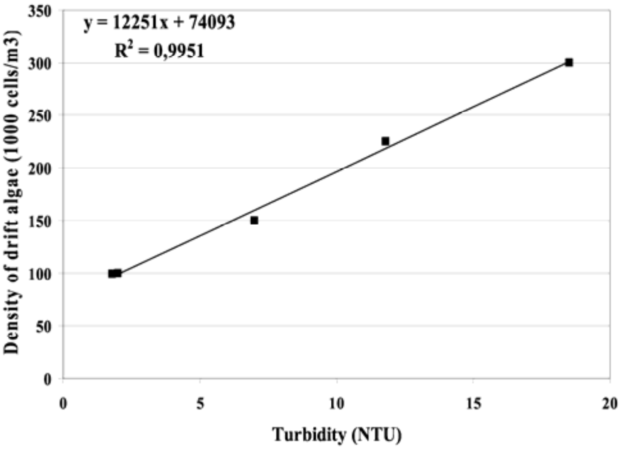

Figure 1: Drift cells density in function of turbidity, Marseille Nord Branch, from Galindo [11].

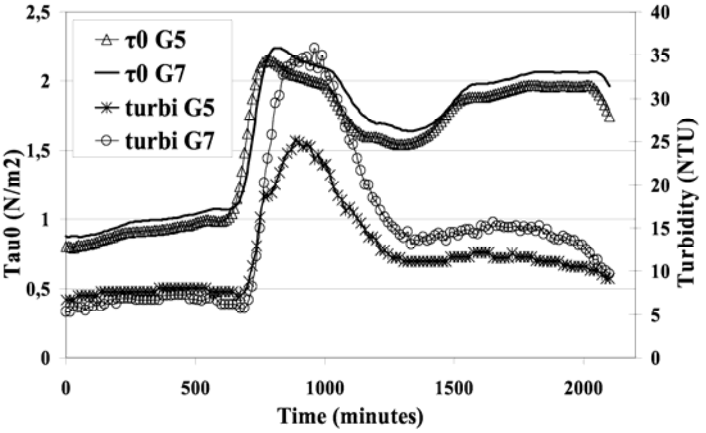

Figure 2: Average shear stress and turbidity evolution, on 24/05/2007, stations of G5 and G7.

Detachment modeling

The critical shear stress was calculated in each section based on average values 15 days before flush. The initial biomass distribution in the canal is difficult to measure.

The first simulations were conducted with a homogenous initial periphyton cover, B_0, throughout the canal. Coefficient β has been fixed to 1. The values of α and B_0 were adjusted in order to minimize the error between simulated and measured turbidities at Vallon Dol, leading to values of B_0= 0.1 g biomass/m2 and α=1 500 s. Results are on graphs a., b. and c. on Figure 3. The evolution is well reproduced at Vallon Dol: the depletion phenomenon appears after the first shear stress increase. After the perturbation we observe a lower turbidity increase which does not appear in the simulation. This can be due to an overestimated depletion or particles re-suspension after possible deposition when shear stress was decreased. However the amplitude of turbidity is overestimated at the other stations. Hence, we can assume a heterogeneous initial periphytic biomass. In a second stage, B_0 was adjusted separately between each station, keeping the initial value of α: B_0 was set to 0.09 g/m2 from upstream to G5, to 0.200 for the portion between G5 and G7 and to 0.170 from G7 to downstream end. The second simulation provides results on Figure 3 d, e and f. We can conclude that the initial periphyton biomass is an important factor when modeling the detachment process and its impact on turbidity.

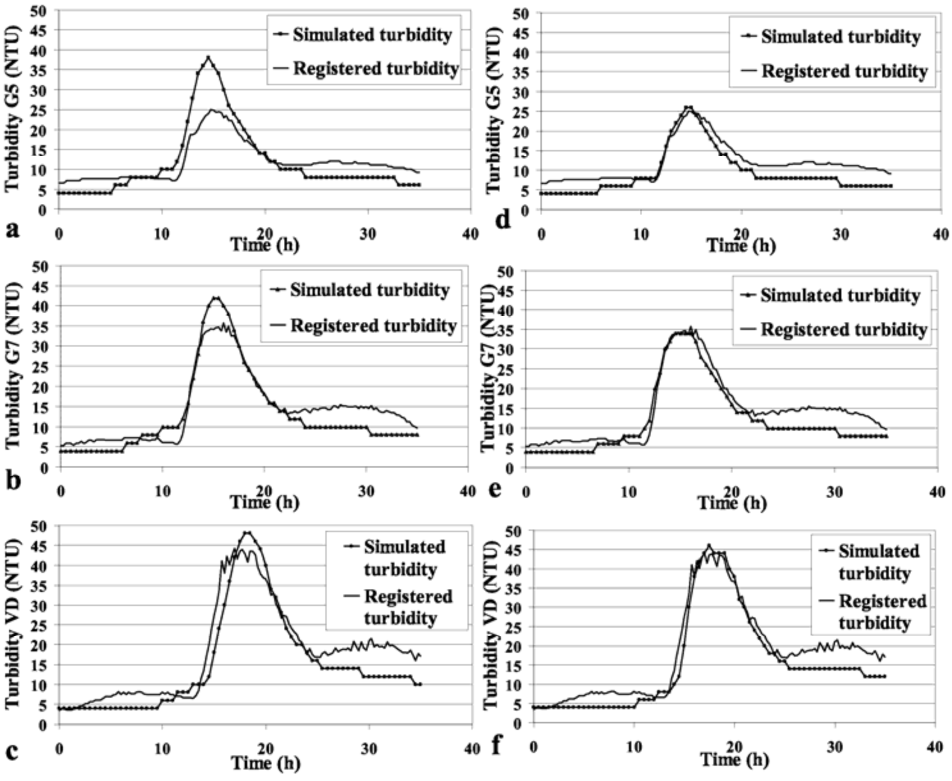

Figure 3: Simulated turbidity due to algal detachment with constant initial periphytic biomass, in a.G5 (19 096 m), b.G7 (22 566 m) and c.Vallon Dol (Downstream), and with variable initial periphytic biomass, in a. G5, b. G7 and c. Vallon Dol , on 24/05/2007.

DISCUSSION

This study shows the potential interest of hydraulic regulation for periphyton control. The hydraulic regulators on the canal enable the manager to generate regular flushes that remove periphyton before water quality is threatened. The modeling approach simulates the relation between the bottom shear stress variations and algae cutting. It represents the periphyton stock depletion and the transport of detached algae.

With the model, the manager can simulate alternative management procedures. The objectives are usually to reduce the volumes used during the flush, maintain turbidity below an acceptable limit and maximize the detached volumes. For instance, the maximal amplitude of the shear stress increases applied in the BMN is not constant for each flush.

This variability suggests that the discharge increases during the flushes can be reduced without loss of effectiveness. Also, the effect of decreasing downstream water levels or closing lateral offtakes during flushes may be easily analyzed.

Turbidity is used as an indirect indicator of drifting algae due to periphyton detachment. It is currently a management criterion easy to monitor. The link between turbidity and drifting biomass depends also on the suspended mineral particles which are not taken into account in this model. It would be useful to have an initial estimation of the fixed biomass in order to get some indication on the periphyton stock evolution. Such estimations require expensive field sampling and lab analyses. Alternative methods would consist in modeling the periphyton growth.

We proposed a new modeling approach for detachment. Since this issue has been little studied in the past, there is room for improvements of the model, but keeping it simple enough to make it usable by managers. The improvements require both hydraulicians and hydrobiologists to work together. Algae resistance and adaptation capacity depends on the species and on the hydraulic conditions during their development [1, 9, 6]. There is a need for further investigations on periphyton sensitivity in canals: determination of the critical shear stress value depending on species and historical environmental conditions. Then biomass production due to algal growth could be insignificant for our simulation periods of one day but it would be necessary to take it into account for longer simulation periods. In particular, simulating the algal growth between the flushes would allow the modeler to estimate the initial periphyton quantity at the beginning of each following perturbation. Thanks to this estimation the calibration of B_0 will be easier.

CONCLUSION

Regular hydraulic flushes are a potential strategy for periphyton control on a canal using cross regulators. The Canal de Provence has been applying this kind of control for a few years in a branch with regular algae removal induced by discharge increase. The perturbations analysis established a correspondence between the bottom shear stress evolution and the algal detachment. This detachment can be indirectly monitored by the water turbidity evolution, which is yet a management variable.

Hydrodynamic models have become essential tools used by managers to improve canal operation, and water quality also needs to be integrated in the management tools. In this paper, we introduce a new model that is able to predict the cutting of filamentous algae fixed on the canal banks (periphyton) and its impact on water turbidity. It highlights the importance of initial biomass cover estimation which seems to be a crucial parameter for the model calibration.

Further research should be done on the model parameterization: determination of the critical shear stress and its link with biological aspects (taxonomy of algae, stage of development, environmental stress), determination of periphytic biomass and sensitivity of algae to shear stress increases. The influence of vegetation on the canal roughness should be studied too.

Such models will be useful to design and improve management strategies and evaluate their performance according to hydraulic criteria (used water volumes, quality of water delivery…) as well as water quality criteria (turbidity, sanitary risks

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