Chapter 6
Transport of Water versus Particular Transport in Open-Channel Networks

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Abstract Hydraulic performance has largely benefited from recent advances in canal control. Nonetheless, taking account of water quality criteria at the same time is more challenging due to longer delay times for particular transport than for wave transport, and to poorly quantified interactions between flow and substratum. This chapter is first illustrated with a typical situation where both water quality and discharge are expected to be controlled. Different approaches of modeling are then introduced, leading to the definition of different delay times that must be considered in the perspective of real-time control. Open-loop and closed-loop control strategies of water quality in open-channels are finally presented and discussed. Research perspectives are suggested regarding combined hydraulic and water quality control.

6.1 Introduction

Hydraulic control of canals has largely been developed in the past 20 years, with many successful applications to real systems, allowing improvement performance regarding hydraulic criteria.

Canals do not only transport water. They also convey different types of elements, some of them being passive, some of them being undesirable when they arrive at check structures or delivery points. This is the case for some dissolved pollutants, floating debris, oil pollution, sediments or phytoplanctonic algae (also called drift). Controlling such transport raises new difficulties compared to water control.

Salinity control appears as one of the simplest problems, although it may be important in some contexts. Problems usually appear in drainage systems in coastal areas when sea level becomes higher than freshwater level. It is rather simple to monitor salt concentration thanks to conductimeters. Based on that, [16] presented

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control methods using either Proportional Integral (PI) or Model Predictive Control for the control of inflow within polders, with both salinity and water level objectives. Compared to hydraulic control, one needs to consider salt transport and dilution, which are well described thanks to the advection-diffusion process. These are also the processes involved in accidental chemical pollutions.

Sediment transport is another type of problem involving particular transport. It may not be a problem if sediments are transported to the cultivated plots, but irrigation networks are usually not able to achieve that. Indeed, channel networks are composed of pools, the size of which decrease from upstream to downstream due to water distribution along the network. With decreasing transport capacity, sediment particles tend to get deposited in upstream portions of the canals. The presence of backwater due to control structures, with large canal depths and low velocity, also decreases the sediment transport capacity and then favour sediment deposition: achieving high hydraulic performance may be contradictory with the objective of minimizing sediment deposition. In this case, the transported class is far from being conservative since most of the particle inflow may be stored in the pools, causing in turn bed aggradation. Also, since sediments are not distributed homogeneously in a canal section, concentrations may evolve at each canal bifurcation [1].

The case of algae cumulates these features. Their growth leads to different management problems, such as clogging of drip emitters, canal roughness variation, and possible toxin release. The interaction between flow and vegetation is difficult to predict accurately, which is a real issue when designing hydraulic management strategies which take into account the disturbances due to algae.

The objective of this chapter is to illustrate operational control methods in which the interplay between transport of water and transport of particles are considered. The case of algae management is used to introduce key issues related to this interplay. Section 6.2 introduces the issues of particle management in open-channel networks and models derived to simulate the involved processes. Section 6.2.4 presents the methods developed to control the transport of particles. Section 6.3 discusses the specific issues related to particle transport management, the interplay with flow control and open topics in this field.

6.2 Case Study: The Management of Algae Transport

Dealing with particular transport implies different time scales. Longer term strategies should prevent the apparition of disturbances by choosing appropriate hydraulic conditions. For example, avoiding sediment deposition requires maintaining sufficient velocities throughout the canals. These conditions may be far from being optimal regarding hydraulic control. Another option is to use transient phenomena in order to eliminate regularly the accumulated particles or vegetation. These events require adapted control procedures, in which both transport of water and transport of particle must be considered. After presenting these strategies, models describing the involved processes are described.

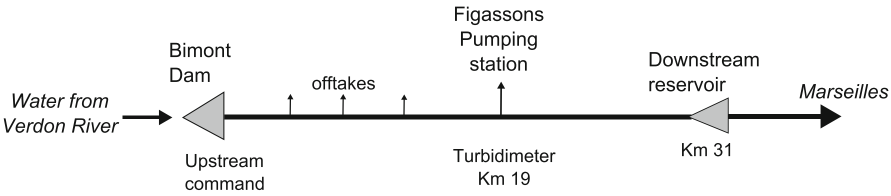


Fig. 6.1 Sketch of the studied portion of the Canal de Provence (Branche Marseille-Nord)

6.2.1 Flushing-Flow Strategies

Flushing-flows consist in increasing flow during a certain time so that shear stress is increased and attached material is moved. This is being practiced in some sewer networks [4] in order to entrain deposited sediments. This results in a turbidity cloud which transported towards the downstream end of the network. This principle has been applied on the Canal de Provence, Branche de Marseille-Nord, in order to detach algal mats fixed on the concrete canal banks. This branch of the Canal de Provence, located in South-Eastern France, is a strategic infrastructure that supplies treatment plants for the city of Marseille, industries and farmers all along its 31 km (Fig. 6.1). The normal discharge in the branch is between 1 and $2\,m^3/s$, out of a conveyance capacity of $3.5\,m^3/s$. The canal is lined with concrete. Check structures are controlled from the SCADA located at Aix-en-Provence. To perform a flush, a flow increase is obtained by releasing water from a dam during a few hours. In this case the released volume is stored in another reservoir at the end of the branch. These flushes allow the canal managers to maintain a constant algal population. Biological analyses have demonstrated that the same flushes should be performed every 2–3 weeks [6].

Turbidity is monitored at different measuring stations (upstream, downstream and intermediate). For each flush, the intensity must be sufficient to detach enough material. Since pumping stations and farmers are located all along the branch, this intensity should not be too large in order to keep the turbidity under an acceptable level. The operation must be done at a time when it disturbs a minimum of end-users. All these constraints justify the necessity to develop models able to simulate the effect of a flush on the transported material.

6.2.2 Process Modeling

In open-channel networks, the hydraulic variables are usually calculated by solving the one-dimensional Saint Venant's equations. The control structures between pools and at each water delivery point are taken into account via stage-discharge-opening relationships.

For the transport of particles, a specific equation is needed in order to calculate the evolution of the concentrations throughout the system. Molecular diffusion, turbulent diffusion and dispersion due to velocity gradients are represented in a unique diffusion term. For non-conservative transport, an exchange term is required in the advection-diffusion equation written in a generic form as follows:

$$\frac{\partial UC}{\partial t} + \frac{\partial (U\ A\ C)}{\partial x} - \frac{\partial}{\partial x}\left[A\ D\ \frac{\partial C}{\partial x}\right] - A\ E = 0, \tag{6.1}$$

in which A is the wetted area (m^2), x the distance along the network (m), Q the discharge (m^3/s), D the diffusion coefficient (m^2/s), C the particle concentration (usually in kg/m^3) and E the exchange rate (kg/m^3/s). The resolution of (6.1) needs two boundary conditions, given for instance by particle upstream input and zero-diffusion at the downstream end. At bifurcations, the proportions of materials passing to each downstream branch should depend on the type of material, whether they are floating (vegetation) or moving preferentially near the bed (like sand particles).

In the case of a flush, the exchange rate becomes essential, since it represents the effect of the hydrodynamic perturbation on the material attached to the canal bed or bank. For sediment, it is common to consider that this rate is a power function of the difference between actual bottom shear stress and a threshold shear stress [15]. By similarity with cohesive erosion models, the same type of relation is considered for attached algae [6]:

$$E = \frac{1}{\alpha} B \left(\frac{\tau_0 - \tau_{0,c}}{\tau_{0,c}}\right) \quad \text{if} \quad \tau_0 > \tau_{0,c} \tag{6.2}$$

$$E = 0 \quad \text{otherwise}, \tag{6.3}$$

with α time constant, $\tau_{0,c}$ critical bottom shear stress, τ_0 bottom shear stress, B fixed biomass per unit bed area. Based on field sampling during flushes, it was shown that the turbidity was proportional to the drift algae concentration, with high correlation coefficient.

The coefficients of the above relations can be calibrated thanks to the monitoring of a limited number of flushes. This set of equations can be used for direct simulation, providing essential information for management such as delay times and turbidity dynamics during the flush. An illustration of flush flow simulation is provided in Fig. 6.2, showing flow and turbidity simulation and measurements at different monitoring stations. We can observe the increase of peak turbidity from upstream to downstream, due to algae detachment in response to flow increase.

6.2.3 Simplified Linear Models

The above models have the advantage to provide detailed hydraulic variables and concentrations at any calculation section. The counterpart is the calculation time which limits their use for real-time control (RTC). For RTC, it can be sufficient

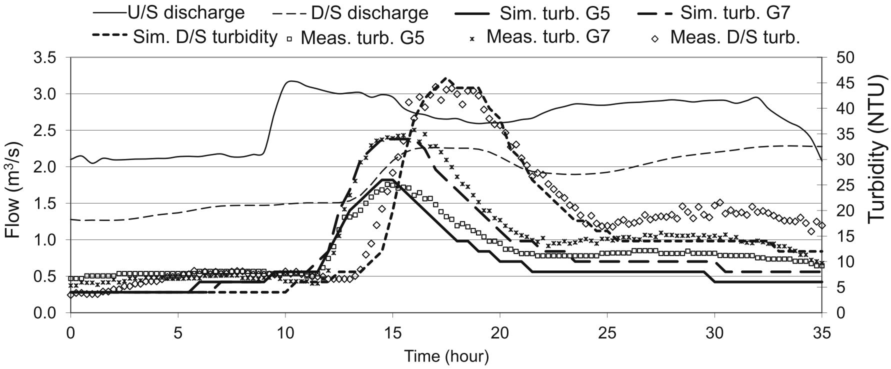
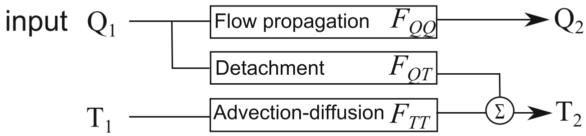


Fig. 6.2 Simulation of turbidity, Branche Marseille-Nord, flush performed in 2007

Fig. 6.3 Transfer functions between upstream and downstream variables (discharge and turbidity)



to write the transfer functions between the input variables (for example the flow entering a canal, or a gate position) and the controlled variables (for example, a water level at a given section). Linear transfer functions are preferable since they are computed very quickly, they can give explicit stability conditions, and under some conditions they can be inverted in order to compute the input that should be applied to obtain a desired response.

In this study case, the input variable is the head discharge, released from a barrage, and the output variable is the concentration at the downstream end of the canal. If the incoming turbidity is not negligible, this turbidity is superimposed to the one generated in the canal. For a canal reach, the downstream response uses three transfer functions (Fig. 6.3):

- F_{QT}, that gives the response of turbidity to the discharge increase;
- F_{QQ}, that gives the downstream discharge variation in response to upstream discharge variation;
- F_{TT}, that propagates the upstream turbidity.

It is useful to have intermediate turbidity variations. To do so, we need to split the canal at the intermediate location, and to calculate the transfer function for each portion of the canal.

Linear models can be derived from the full nonlinear systems of equations. To this end, we first linearize the Saint-Venant and advection-diffusion equations. Thanks to Laplace transforms of the time domain equations, we can obtain explicitly the response at any location, as a function of the input variables. Using approximate transfer functions (first or second order with delay), we obtain simplified transfer functions that can be used for RTC. Based on the approach described in [10], polynomial transfer functions with delay can be derived [8]:

$$F_{QQ} = \frac{e^{-\tau_Q s}}{1 + K_Q s}, \tag{6.4}$$

$$F_{TT} = \frac{e^{-\tau_T s}}{1 + K_T s}, \tag{6.5}$$

$$F_{QT} = \frac{G_D}{1 + K_D s} \left(F_{QQ} - F_{TT}\right), \tag{6.6}$$

with s the Laplace variable. The first two transfer functions have different delays (τ_Q and τ_T) corresponding to hydraulic propagation and advection-diffusion. The time constants K_Q and K_T represent the hydraulic attenuation and the diffusion. These coefficients can be obtained from the properties described in the full nonlinear equations. The time constant K_D expresses the sensitivity of the attached material to the discharge increase. The gain G_D of F_{QT} is sensitive the quantity of material that can be detached during the flush. It also includes the linear correspondence between algal concentration and turbidity. This gain can hardly be defined by a deterministic approach.

Equation (6.6) cannot be inverted analytically in the time domain. A more compact form was proposed in [7]:

$$F_{QT} = \frac{s\gamma_0 e^{-\tau_D s}}{(1 + K_{D_1} s)(1 + K_{D_2} s)} \quad \text{if} \quad dQ_u/dt > 0, \tag{6.7}$$

$$= 0 \quad \text{otherwise}, \tag{6.8}$$

in which Q_u is the upstream discharge. In the time domain, the differential equation which gives the turbidity is

$$K_{D_1} K_{D_2} \frac{d^2 Tb_d}{dt^2} + (K_{D_1} + K_{D_2}) \frac{dTb_d}{dt} + Tb_d(t) = \gamma_0 \frac{dQ_u}{dt}(t - \tau_D). \tag{6.9}$$

This quasi-linear model is easy to implement under calculation tools or spreadsheets, so that the four parameters K_{D_1}, K_{D_2}, τ_D and γ_0 representing the turbidity response to a flush can be easily identified from field measurements. Among these parameters, the first three ones are expected to remain constant for all flushes, while the gain γ_0 will vary with the attached biomass. Adjusting this gain can be done thanks to the expertise of the manager (as done at the Canal de Provence, see Sect. 6.2.4), or in real-time using appropriate controllers (see Sect. 6.2.4). Illustrations of the model performance are presented in [7].

6.2.4 Real-Time Control of Particular Transport

Open-Loop Control

In order to design a flush, one needs to define how much water should be released, at what time and for how much time. The higher is the released discharge, the larger is the shear stress increase and the more biomass is detached.

Yet, impacts must be considered: the hydraulic disturbance affects the water quality for some time, and it also causes undesirable water level fluctuations. In practice, most of these disturbances should occur during the night, when water demand is the lowest, so that pumping stations can be stopped if the turbidity is excessive.

Hydraulic disturbances can be anticipated using Saint Venant's equations-based models. It is not simple, however, to determine the flow release that is necessary to achieve a given downstream discharge objective, as the inversion of the Saint-Venant's equations is an ill-posed problem [5]. There are also some physical limitations, mainly due to the attenuation during flow propagation. Linear models offer an alternative for hydraulic inversion, such as a first-order with delay derived from Saint-Venant's equations with offtakes [13].

For water quality management, the inversion of the system of three equations is again an ill-posed problem. Here, the objective is to reach a given turbidity which guarantees that attached material has been removed from the canal banks. It is also expected not to overcome this targeted turbidity in order to avoid clogging problems at the hydraulic devices.

The linear transfer function (6.9) can be used to compute the upstream discharge $Q_u(t)$ from the desired downstream turbidity. Practical curves can be derived from the model, such as the flush duration or the amplitude of the discharge increase. For the flushes performed at the Canal de Provence, the following principles are used:

- the gain of the model is adapted with experience, based on the gain obtained for previous flushes
- discharge must be increased by about 60 % in order to reach the threshold that will initiate algal detachment
- then, the discharge is increased linearly until the maximum is reached, as defined by the discharge-turbidity transfer function.

These concepts have been used to design the feedforward controller which calculates a priori the command u_r to apply (see Sect. 6.2.4, Fig. 6.4).

Closed-Loop Control

Most of the operational control methods of irrigation canals are based the well-known linear PI controller. The calibration of the controller parameters must fulfil two contradictory objectives: reactiveness and stability. This calibration is

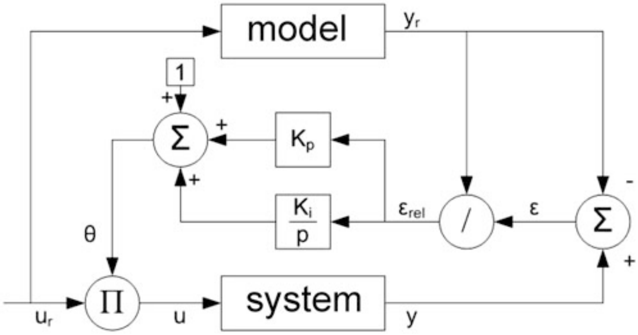


Fig. 6.4 Adaptive control as implemented at SCP (Branche Marseille Nord)

usually done by trial-and-error method. Due to the delay between action (upstream discharge) and system response (downstream turbidity), one may be tempted to increase reactiveness by increasing the proportional gain of the controller. This may cause undesired oscillations. When dealing with water quality, the delay is much larger than for hydraulic transfer, so the risk of instability is larger. The issue of delay times is discussed in the next section.

A second big issue is the large uncertainty when defining the transfer function gain between discharge and turbidity F_{QT}. When only hydraulic transfer is considered, the gain between upstream and downstream discharge is close to unity. It is a bit smaller if withdrawals are larger than supplies from intermediate tributaries, and larger than unity in the opposite case. Monitoring systems are usually installed at stations where large flow changes are likely to occur, so that the transfer function gains can be quite correctly estimated. Regarding quality control, there are cases where the situation is similar, for example when dilution is the main process governing the evolution of a solute concentration. This is the case for salinity control, as described in [16], in which it is shown that PI controller is able to maintain a desired salt concentration. The case of sediment or algae flushes is far more complex, since the downstream response to a discharge increase is mostly due to the interaction between the substrate and the flow, so that the flux of particles is far from being conserved between upstream and downstream sections. In the extreme case, one can have clear water at the upstream control section (concentration is 0), while downstream concentration can be large, due to internal erosion processes. In this case, the exchange process is a predominant term in (6.1), which will determine the gain of the transfer function. To date, there is no universal model which is able to predict with a good accuracy the erosion rate of non-cohesive sediment. This is even worse for cohesive sediments and algal biofilms, for which chemical and biological properties increase the complexity of the cohesion processes. For efficient flushes, another problem is that the material which can be eroded decreases with time during the flush, so that the gain of the transfer function is likely to decrease.

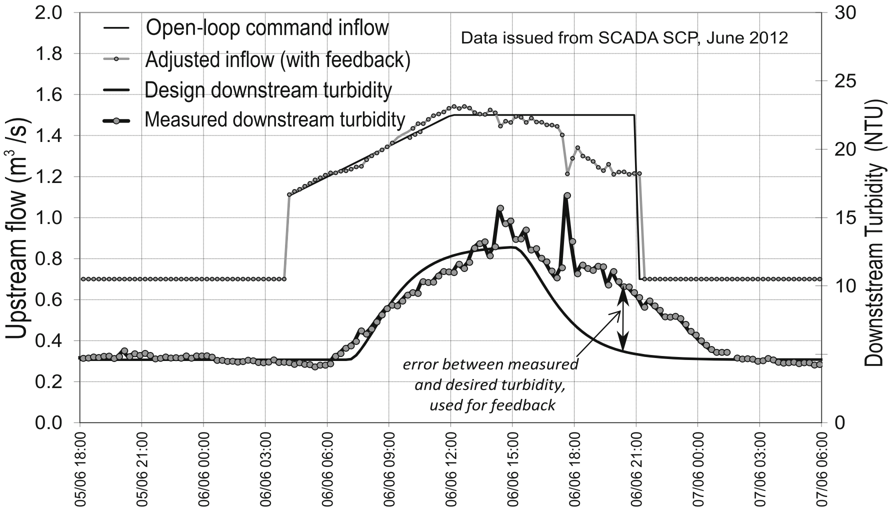


Fig. 6.5 Flush performed in June 2012, Branche de Marseille Nord (Canal de Provence), between Bimont dam and Figassons pumping station (km 19)

Adaptive control, which was designed to control systems with slowly varying gains, looks adequate for the real time control of flushes expected to cause erosion. This was implemented at the Canal de Provence and applied in routine since 2012. The controller is presented in Fig. 6.4. The initial command inflow (u_r) is given by the open-loop controller. During the flush, the relative error on the downstream turbidity is used to adapt the proportional and integral gains of a PI controller that will adjust the released flow by multiplying the initial command u_r. The correction θ takes account of the error of the transfer function (inaccurate initial gain), and to the adaptation process itself (decrease of erodible material during the flush). A speed of adaptation is also defined, which conditions the stability of the controller.

Figure 6.5 shows the performance of the flush performed in June 2012, with data extracted from the SCADA of the Canal de Provence, stations Bimont (upstream dam) and Figassons (control point 19 km further, with pumping station). Four curves are presented: open-loop flow command (u_r), adapted flow u, expected turbidity at downstream section, which is the result of the open-loop transfer function applied to u_r, and measured turbidity. One can see that the model response of the model was very good, in terms of delay and attenuation, during the first 13 h after the start of the flush. During this period, almost no correction was necessary (θ close to 1). Then, observed turbidity is greater than the expected one. This leads to decrease the command inflow. The flush is stopped after a regular decrease of the turbidity is observed, and the initial turbidity is recovered after about 3 h.

6.3 Discussion

6.3.1 Managing the Transport of Particles: What's New for Hydraulic Control?

Controlling the transport of particles in regulated open-channel networks open new perspectives for canal control. The example of algal management illustrates some of these perspectives, some parallels that can be drawn between the control of hydraulic variable and the control of quality variables, but also some new issues raised by the interplay between both problems. These perspectives are discussed below.

Does Quality Management Require a New Control Framework?

We have seen in the above example that the framework developed for hydraulic control can be extended to water quality control. Following the classification introduced by [11], Table 6.1 summarizes the framework which was applied to design the control of water quality during flushes, in parallel with the one used for hydraulic control.

Does the Superposition of Various Dynamics Makes the Control Problem More Complex?

A main issue with canal control is the delay between an action, for example a gate movement, and the expected result of this action. When you release water at the

Table 6.1 Summary of the control frameworks for hydraulic and quality

	Hydraulic control	Water quality control
Controlled variables	Flow, water level	Turbidity, concentration
Control action variables	Gate position, flow	
Process modeling	Saint-Venant's equations (SVE)	Advection-dispersion, SVE
Main uncertainties in transfer functions	Withdrawals, ungauged supplies	Erodible material, interplay between hydrodynamics and substrate
Real-time modeling	Linear models based on linearization of above equations, e.g. first or second-order with delay equations	
Control logics	Feedforward and feedback, upstream and downstream control	
Performance objectives	Satisfactory flow distribution, limited level fluctuations	Limitation of risks regarding quality and particle load, of hydraulic disturbances
	Limitation of operation and maintenance costs	

head of a canal, it will take time for the wave to arrive at a downstream section, and it will take more time to obtain the discharge which has been released, due to attenuation during flow propagation. These times do not only depend on the canal cross section characteristics, but also on the control structures which cause a backwater, and feedback between flow variation and level variation [14]. In practice, managers must consider the delays when planning gate operations in order to satisfy a delivery schedule. The optimal delay (or "response time") is the one which will ensure that the released volume is delivered to the targeted offtake [2]. This time is about 8 h for the Branche de Marseille Nord, between Bimont Dam and Figassons.

Regarding quality, one needs to consider other delays, such as the travel time of particles (denotes T_p) or the travel time of a turbidity cloud. During a flush performed with an upstream flow release, the discharge increase will cause erosion in the upstream section, then the corresponding turbidity is transported at the bulk velocity. The hydraulic wave also propagates downstream, more rapidly than the particles of water causing erosion. The superposition of all these phenomena makes it difficult to calculate the delay times between flow release and turbidity response. This turbidity response is also characterized by a time of arrival, greater than the travel time of surface waves (T_{sw}), and a peak time, which in our study case corresponds to the travel time of particles. The definitions of these times are summarized in Table 6.2. They can be easily obtained by simulation, as illustrated by Fig. 6.6 for the Branche de Marseille Nord. The travel time of particles is much larger than the others. These hydraulic times can be related to the parameters of the simplified transfer functions:

- The delay τ_Q is close to T_{sw};
- $\tau_Q + K_Q$ corresponds to the travel time of long waves T_{lw} [2];
- similarly, $\tau_T + K_T$ corresponds to the travel time of particles T_p. In our case, it also corresponds to $\tau_D + K_{D_1} + K_{D_2}$.

A second key issue is the uncertainty inherent to the erosion processes:

- The existence of a threshold before erosion can occur is likely to increase these delays.
- There may be a large spatial variability of the material likely to be flushed. If, for example, no algae or no sediment were present in the downstream reaches, then no material would be detached and entrained when the wave arrives. This also delays the response.

Table 6.2 Definition and calculation of hydraulic times, for a reach between abscissas x_1 and x_2

Travel time of particles	$T_p = \int_{x_1}^{x_2} \frac{dx}{U}$	U mean flow velocity
Travel time of surface waves	$T_{sw} = \int_{x_1}^{x_2} dx/\left(U + \sqrt{gA/B}\right)$	g gravity constant, B top width, A flow area
Travel time of long waves	$T_{lw} = dV/dQ$	V volume of the reach, Q mean discharge in reach

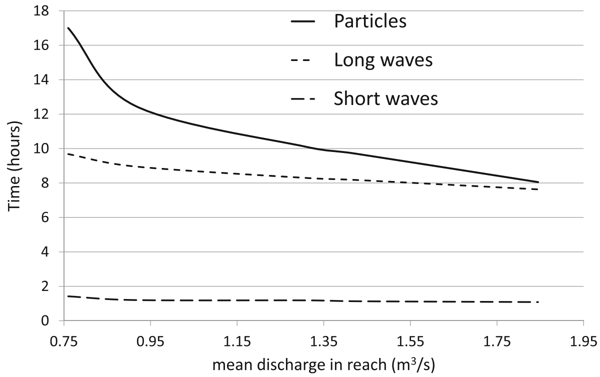


Fig. 6.6 Delay times, Branche de Marseille Nord, between Bimont Dam to Figassons. The x-axis corresponds to the mean discharge in the reach. Simulations are done with SIC

The superposition of all these aspects makes it difficult to identify the main processes that need to be considered when managing the canal system.

6.3.2 Estimating the Performance of Control Strategies

Managing algal issues by hydraulic methods has been innovative, and the evaluation of the strategy is a frequent question. Two time scales must be considered to start addressing this issue.

On the short term, we must evaluate the performance of a flush. To do so, standard hydraulic criteria could be used, such as Mean Absolute Error or Integral of Absolute Error [3] or released volume, which, in some cases, may be lost if it is not stored downstream. Since the primary objective of the flush is to detach fixed material, it makes more sense to build an indicator reflecting the efficiency of the flush. To do so, it is preferable to use the integral of turbidity at the downstream end, I_T, which can be calculated explicitly as a function of the flush parameters (discharge increment and duration) [7]. Then the open-loop model was build by maximizing I_T with the constraint that turbidity does not overcome a given threshold. For example, for the flush of Fig. 6.5, I_T is equal to 90 NTU.hr, which 1.38 times the value initially used for the design of the flush. This indicator indicates that the flush has been as efficient as expected. It also suggests that the initial biomass was under-estimated.

In this case, no hydraulic performance indicator is considered. This was not a problem since flushes were performed during the night when water demand was the lowest. However, in some other cases, water level fluctuations may be an issue for gravity offtakes. This would lead to build multiple criteria in order to take account of both turbidity and hydraulic objectives. These objectives are antagonistic, since larger detachment efficiency will implies larger hydraulic disturbances. The design of the control method and the performance evaluation then requires writing the optimization problem with an aggregated performance measure, and constraints with both turbidity and hydraulic variables. The performance measure may be written as a weighted combination of I_T and hydraulic performance indicators, such as normalized errors on water levels, with weighing factors set by experience of the manager.

On the long term, the performance must be measured with more integrative criteria. Regarding the issue of algae development, since it is hardly feasible to get direct measurements of biomass, indirect estimations of the performance can be obtained by registering the disturbances caused by algae, such as filters clogging, increase of water levels due to increased bottom friction, etc.

6.3.3 A Unified Framework for Transport of and over Water?

The example of algae management illustrates the idea that multiple (and sometimes antagonistic) objectives may be searched while controlling hydraulic structures. In this study case, a unified framework was applied for both quantity and quality management, with three main components: building appropriate models for each of the considered processes, defining performance indicators, and then designing appropriate controllers.

The interplay results from the fact that the same hydraulic variables are involved. For instance, the flow velocity needs to be increased in order to detach algae, keeping the water levels high enough so that algae present on the banks remain in water during the flushes. This increase of velocity therefore causes an increase of discharge, and thus an excess of flow passing through the system. Regarding transport over water, flow velocity is also a key variable that will be used to express the fluxes of boats, while water levels must remain within a desired range. We can see some evident parallels with the issues of flushing flows.

Therefore, we think that a unified framework can be applied for the control of waterways regarding transport of water and transport over water. This supposes to develop appropriate models for each of the processes, and then controllers using either hydraulic variables, or other variables that can be measured in real time such as turbidity or transport loads. Performance indicators must be properly designed and weighed, in case multiple objectives need to be achieved at the same time.

6.3.4 Open Topics

Understanding and managing the interplay between hydraulic control and water quality requires improving our representation of the involved processes. Among these processes, the effect of hydrodynamics on the biological substrate is the one which introduces the most uncertainty in the exchange term of advection-dispersion (6.1). Local studies, with fluid mechanics tools, can give an insight on the basic processes, the key variables, the thresholds required to obtain the detachment of an algal filament, …Nevertheless, at the scale of the studied system, we are not able to go into such detailed representations, and it is reasonable to choose integrative variables such as mean biomass and mean critical shear stress. Based on that, (6.2) seems appropriate to represent the exchange term. Still, the time constant and the critical shear stress depend on the biological substrate.

Also, large uncertainties remain however on the transfer function between discharge and turbidity. Turbidity response is directly proportional the detachable biomass which a key state variable. As physical sampling is hardly feasible in an operational context, indirect measurement methods based on a combination of sensors could be a solution. Conversely, the vegetation growth may dramatically increase the roughness, causing overflowing in some extreme cases. Although laboratory-scale studies have brought an inside on this issue [9], the link between global biomass and hydraulic properties still need to be explored. There is room today for many fruitful interactions between hydrobiology and fluid mechanics [12]. While most of the studies are performed in river contexts, some issues are very specific to regulated open-channels, such as the flow variations imposed by gate operations, or the way detached material are transported from upstream to downstream, passing or not check structures and bifurcations.

The control structures give also the chance to manage vegetation and water quality at the same time as water volumes. This leads to consider multiple management objectives and constraints, to consider new performance criteria, and to develop new methods able to address the specific issues of water quality control. For real time control during a flush, adaptive control was a way to deal with large uncertainties on initial biomass, and re-estimate this biomass in real time. Other frameworks may be worth studying, such as model predictive control (as used in [16] for salinity control), with data assimilation for real-time estimation of biomass, and performance criterion aggregating quality and hydraulic performance.

6.4 Conclusions and Future Research

With the diversification of uses of the hydraulic infrastructures, which is pushed by integrated water management objectives, it is necessary to adapt the hydraulic management strategies of these systems with adapted indicators and rules. We have shown a study case in which hydraulic management is expected to control complex water quality aspects: in order to control the fixed algae populations, flushes are performed regularly in a multi-purpose open-channel network, a strategic infrastructure for agriculture, industries and domestic water in South-Eastern France; during a flush, water quality is controlled in real-time thanks to advanced automatic command methods.

This example has illustrated issues linked to the interplay between concurrent objectives. The complexity of the management is largely increased by the superposition of different processes, with multiple delays and attenuation dynamics between action and system response. These issues have raised new questions about modeling (comprehensive models and simplified more adapted to real-time control), and about management methods able to address uncertainty and multi-objective criteria. Some of these questions will be raised by the interplay between transport of water and over water.

Further research will continue the efforts to characterize the links between hydraulic management and water quality, with an increased focus on aquatic plants which, like algae, are subject to withdraw nutrients from the water bodies but also cause very large friction. This requires considering larger time scales, with seasonal evolution of biomass and impact of hydraulic control on nutrient cycles.

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