MODELING, CONTROL AND DATA ASSIMILATION ISSUES FOR OPEN-CHANNEL HYDRAULIC SYSTEMS - WHAT TO DO WHEN WE CAN'T GET NO SATISFACTION FROM MINIMIZATION?
– **Keynote Lecture** –

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Several types of natural or artificial open-channel hydraulic systems are managed (here taken in the sense of "operated") in order to satisfy some operational constraints, in presence of external (often unknown) disturbances, and using some real-time measurements on the systems. This general description already introduces the underlying concepts of modeling, control and data assimilation. The objectives of this presentation are (i) to present the problems to be solved on a mathematical point of view but also with some real-case illustrations, (ii) to present some solutions of these problems, (iii) to show the logic of the links between these modeling, control and data assimilation issues which are usually studied in different academic communities, (iv) to make a focus on some problems we face when using classical minimization approaches, provide (partial) solutions and leave some still opened problems for discussion. The illustrations will be given on different classes of open-channel hydraulic systems, such as sewage systems, irrigation canals and rivers.

Sewage systems are usually operated in order to extract the "water" from the system to the treatment plants, in order to prevent overtopping, which can be a big challenge at daily peak flows and specially during storms. One key issue on this type of system is to reduce the accidental releases into the natural environment, and therefore to maximize the use of the available storage volume and treatment capabilities of the sewage plants.

Irrigation canals are operated to convey water from upstream source(s) (dam, river) to users (agricultural lands, but also industries and cities, recreational activities, environmental water bodies, etc). Such systems can be very large: several hundreds of kilometers of canals, several hundreds of m^3/s of nominal flow (ex.: South to North transfert canals in China, Narmada canal in India, Philippe Lamour (BRL) canal and Société du Canal de Provence canals in France). Varying objectives are assigned to their managers. The main general one is to provide water to the different users at the right moment and in the right quantity, to minimize water losses, and to guarantee the safety of the infrastructure. In particular, a major concern is to prevent the canals from overtopping, but also from having water levels inside the pools below the supply depths of the gravity offtakes.

Some rivers, such as the Rhône river, have similarities with these canals in the sense that hydraulic devices (hydropower plants, dams, locks) are located along the course of the river and operated in order to produce hydroelectricity, insure water levels compatible with navigation constraints and limit the negative impact of floods.

An efficient way of operating these structures, specially using automatic controllers, allows to improve the overall performance of the system, and to reduce civil engineering costs (additional reservoirs, size of the system, maintenance of damaged banks, etc). All these systems have in common the fact that they convey water, in open channels, therefore governed by the same underlying equations

(Saint-Venant equations). The 1D version of these equations is generally sufficient for such systems. These equations are nonlinear hyperbolic partial differential equations [1].

Some simple control algorithms can be automatically tuned directly on the real systems (e.g.: PID with ATV method), without requiring (explicitly) a model of the process to control. But, most of the more advanced approaches, specially MIMO (Multi-Inputs, Multi-Outputs) ones, need a model of the system, to design and tune the controller. This model, like in any project using a model, needs a calibration phase. For a 1D hydrodynamic model based on Saint-Venant's equations, this often means adjusting roughness coefficients, discharge coefficients at cross and lateral devices, and seepage. Several methods are described in the literature, based on minimization approaches. Whatever algorithm selected, there is nevertheless an important question to address first, which is seldom studied in the literature: "is it possible to identify the parameters I want from the measurements I have?" This first question is linked to what is called "sensitivity". This depends on the relationship between parameters and outputs of the model, but also on the desired precision on the parameters and on the available one on the measurements. Some people introduced the concept of "equifinality" stating that, in some cases, several different sets of parameters give the same model outputs within given uncertainties. This concept is somehow peculiar in the sense that it is used to criticize the model (structure and/or parametrization) itself, whereas it may also be attached to the set of data used for the calibration. An important question is therefore "what type of input scenario would be best (or at least required) to be able to calibrate the model?" This second question can be addressed under some assumptions using the "worst-case" concept. We will present methodologies for answering these 2 questions, and apply them on an example taken from the literature. This shows that having a minimization algorithm is maybe useful, but being able to answer the 2 above questions is even more important [6].

After having obtained a ("good") model, a controller can be designed and tuned (structure and parameters choices). "Good" model is very relative, and not well defined. If the uncertainties on the model can be assessed, the "robust control" approaches can explicitly take them into account during the controller design and tuning phases (ex.: $\mathcal{H}_\infty$, μ analysis, ℓ_1 frameworks). There exist a large spectrum of control methods that have been tested on open-channel hydraulic systems [9]. The one we will present here is based on the ℓ_1 norm minimization. This is justified by taking into account some classical objectives and contraints imposed in the specifications of the controller. One main objective is to minimize the deviations of an output variable around its targeted value. This can be written as minimizing the (ℓ_∞ norm) of some controlled signals z. The cross-structures used as actuators have, also, minimum and maximum allowed gate openings. These constraints are typically time-domain constraints on the bound (ℓ_∞ norm) of some controlled signals z (the z can include some u as we will choose to do). On the other side, a bound on the perturbation w is also known (e.g.: subscribed maximum discharge at offtakes, inflows at tributaries, discharge surges due to the start or stop of a turbine, released volume from a lock), which is also an information on its ℓ_∞ norm. This justifies the idea to design a controller by minimizing the ℓ_1 norm of the impulse response of the considered transfer matrix $\Phi : w \to z$, since this norm is the induced ℓ_∞-ℓ_∞ norm [2, 5, 10]. In addition to the minimization of this norm for some transferts, bounds can be also specified on some of them.

By default, without additional specific care, the obtained ℓ_1 controller does not include integral effects, meaning that steady-state errors can occur. This does exist despite the fact that the controller has been designed minimizing some norm on the outputs to be controlled. We could have naively thought that this minimum would lead to zero steady state-error, but unfortunately it is not the case. This is usually a problem, since the control objectives very often include maintaining a given water level at some strategic point as close as possible to its target. A manager cannot be satisfied by just knowing that is has been somewhat minimized. He wants to have the guaranty that the error (by example between a water level and the corresponding target) will converge towards zero, at least when the disturbances have reached a new steady-state. We will present the principles of the ℓ_1 controller design and show its performances on some bench-mark canal [8]. We will then focus on the introduction of such integral effects into this ℓ_1 controller design. Four different options will be described and compared, the more interesting one being based on the introduction of a time-domain template [7].

After this design and tuning phases, when the controller is available, the computation of control actions at actuators is based on measurements at some characteristic points (feedback control). These measurements can be water levels as well as flows along the hydraulic system and/or at the hydraulic devices. Thus, when failures of sensors occur or during strong transients (such as stopping or starting the hydro-power turbines, large change of the water distribution, etc), the regulation process can be disturbed. A solution suggested to detect sensor defaults, to correct the observations and to update the water profiles involved in the calculation of control actions, is based on a data assimilation method (e.g.: Kalman Filter). This method is optimal because it ensures minimizing the estimation error (the trace of the covariance matrix of the a-posteriori state error to be more precise). But (again!) this property is not sufficient for some industrial applications, and in particular in our case. This is why the notions of detectability and convergence of the Kalman Filter have been studied into more details. This study has identified sufficient conditions that ensure the error of the estimate to converge towards a nil average. This issue will be illustrated on a portion of the Rhône river between 2 hydropower plants. In order to test and validate such a method, it has been implemented into the industrial test tool of the Compagnie Nationale du Rhône called "simulation platform" [3, 4]. Examples of usually difficult scenarios simulating a loss of sensor and an unexpected stopping of a turbine will be presented. The reconstruction of unmeasured inflows at tributaries will also show the importance of the number and location of the sensors, allowing (or not) this reconstruction. It allows demonstrating the benefits of the presented solution, and the fact that the minimization used in the Kalman Filter is not always sufficient.

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