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Improved Modelling of hydraulic works including run-of-the-river dam in TELEMAC

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Abstract - **In their vicinity, hydraulic works can lead to fast and multiple transitions from subcritical to supercritical flow regimes. Therefore, modelling weirs or gates or run-of-the-river dams by meshing their 3D geometry makes computations particularly responsive to the flow instabilities and therefore to unsatisfactory simulations. A classical technique to overcome that difficulty consists in the use of specific laws inspired from 1D modelling such as relationships between the flow rate, Q, and the dynamic head, H, estimated upstream and downstream the hydraulic works. Such modelling was often proven to be more relevant than geometrical modelling.**

To correctly implement such laws in TELEMAC (2D and 3D), we represented the hydraulic work as a hole in the mesh. This hole is delimited by a polygon with two opposed boundaries where flow rate boundary conditions are imposed. The imposed flow rate is computed at time step n from the specific laws thanks to the hydraulics conjugate variables read in two control sections located upstream and downstream the hydraulic works at time step n-1. Additionally, we implemented guidelines about control section location, bed geometry, flow regime determination and relaxation to avoid most of instabilities during computation.

This implementation of the structures as hole in the mesh allowed us to add in a second time an option which takes into account the PID controller that regulates flow passing into the Dam in normal time. The outflow is made dependent on a set point at a precise location. This addition makes possible to model the behaviour of the structures in any flow condition.

Finally, we tested this implementation on Donzère-Mondragon reach, which contains four hydraulic works: the local dam ensuring the water level regulation and three keeping dams made to prevent high water level in the power plant channel. Those four dams operate at different time, depending on the flow. We simulated the 1,500-year flood (as an unsteady flow) to test our model.

I. INTRODUCTION

1D simulations are commonly used to model floods in complex hydraulics developments such as those operated on the Rhône River. Nevertheless, as a consequence of advances made in computation and topography's data, 2D and 3D models are increasingly becoming a standard. In this article we deal with the modelling of hydraulic structures in 2D and 3D studies.

For 2D or 3D computations, hydraulics works such as weir or dams (when they are open), need to mesh hydraulic works much more precisely to account for the transient nature of the hydraulic work. As a result, this type of modelling is very costly in term of computational time. Moreover, it makes the opening and closing of gates more complicated.

The solution proposed in this paper is to model each hydraulic work as a hole in the mesh. For each of these holes, we add two opposed boundaries in which flow rate is prescribed by laws depending on hydraulics variables. We created additional module for TELEMAC based on previous work [1] and applied it on 2D model of Donzère-Mondragon Reservoir (DM). The development integrates specific works to protect the 17 km long channel to a power plant. The DM Reservoir was chosen for its complexity which enables to test the robustness of the code. In a first approach we implemented the weir laws and modelled the dams as weir which is relevant for particularly high discharges when dams are fully open. In this case inflow and outflow are computed from water level and velocity. In a second approach we added a regulation system which models normal operations, including adaptative opening and closing of the dam gates. In this case, total flow leaving the reservoir is controlled by the water level at a specific location upstream. The total flow is shared between the dam and a hydropower plant depending on their characteristics (a regulation law is defined for each reach).

This article presents firstly theoretical support used to implement subroutines, then we present the Donzère-Mondragon Reservoir and the associated model. Thirdly we detail the subroutines implemented and finally we present the results and limits of the method.

II. THEORETICAL SUPPORT

A. *Integrate 1D hydraulic laws in 2D/3D*

The main hypothesis of this study is to consider that flow over hydraulic works can be described by 1D laws. Therefore, we implemented dedicated 1D laws to model works, and we computed average quantities over cross-sections to estimate equivalent hydraulic 1-D variables such as the water level or the discharge. Another solution would be to use directly 2D or 3D variables and to represent hydraulic work node to node with weir laws, but this does not allow the work to be considered as a whole and thus to integrate hydraulic controls.

B. *Notations*

We defined then the necessary 1-D hydraulics variables used to compute flowrates. We obtain them by computing integration of 2D or 3D ones over a determined cross section. The physical quantities are considered in three sections: an upstream control section (am), a downstream control section (av), and the hydraulic work section (s). The elevation of weir crest is denoted by Zseuil and the top of gates is denoted by Zsup.

We note:

- Zam = water level elevation in the upstream control section.
- Zs = water level elevation at the hydraulic work.
- Zav = water level elevation in the downstream section.
- Zr = water level at at the regulation section
- Zc = water level set point

Each quantity defined afterwards is considered at the various places with the suffixes (am, av, s, c, r). Q is the water flow over the weir. V is the average velocity of the flow in any specified cross-section denoted by S. S can be different of the hydraulic work section s. In every section S, we have V = Q/S. For every section S, the water depth is computed relatively to the weir crest:

$$y = Z - Z_{seuil}$$

And dynamic head above weir crest:

$$H = y + \frac{V^2}{2g}$$

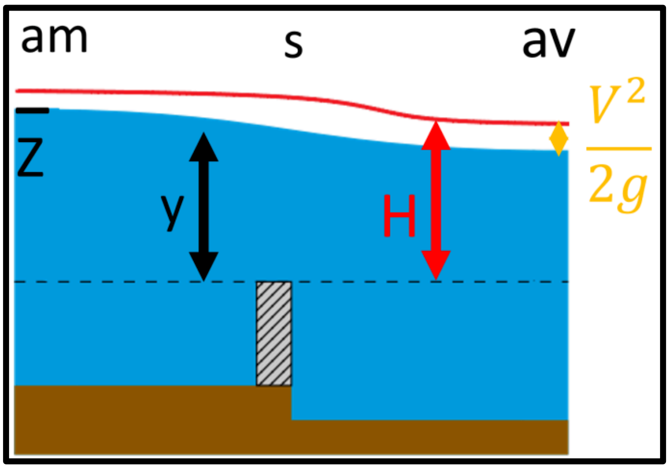

Figure 1. Notation diagram for a weir

C. *Weirs and gates laws*

The weir laws available in the literature can mainly be classified in 2 categories either if the discharge is computed from i/ the water level, Zam and Zav or ii/ the specific energy Ham and Hav. Here, we chose to consider the specific energy upstream [2] even the increased risk of computation instabilities. These equations derive from energy conservation [3]. In supercritical conditions, weir laws are written:

$$Q = C_{seuil} \times L_{seuil}\sqrt{2g}\frac{2}{3\sqrt{3}}(H_{am})^{\frac{3}{2}}$$

With C_{seuil} the weir conveyance coefficient and L_{seuil} the weir width. Then in subcritical conditions:

$$Q = C_{seuil} \times L_{seuil} \times y_{av}\sqrt{2g}\sqrt{H_{am} - y_{av}}$$

Supercritical condition's gate law is:

$$Q = C_{seuil} \times L_{seuil}\sqrt{2g}\frac{2}{3\sqrt{3}}(Z_{sup} - Z_{seuil})\sqrt{H_{am} - (Z_{sup} - Z_{seuil})}$$

And subcritical gate law:

$$Q = C_{seuil} \times L_{seuil} \times (Z_{sup} - Z_{seuil})\sqrt{2g}\sqrt{H_{am} - y_{av}}$$

D. *PID Regulation*

The PID is an automatism (with three corrector terms: proportional, integral and derivative) designed to set the water level Zr to a set point Zc at a specific location named the regulation section (PR) by adjusting the total flow out of the system. We have thus Q = f(Zr – Zc). The function f is the sum of a proportional and an integral corrector which provides a correction of the measured deviation Zr - Zc. A derivative term is added to anticipate future disturbances.

III. STUDY CASE

A. *Donzère-Mondragon Reservoir*

Donzère-Mondragon Reservoir is the second oldest CNR reservoir, located near Bollène in the south of France. All the reservoirs on the Rhône River but one are operated by CNR following the same pattern. The site includes a reservoir, contained by with dikes, a diversion channel also contained within dikes and closed by a hydropower plant (here the power plant of Bollène - USB). Finally, the water level in the reservoir is controlled by a dam, here the Donzère run-of-the river Dam (BGRT), equipped with mobile gates.

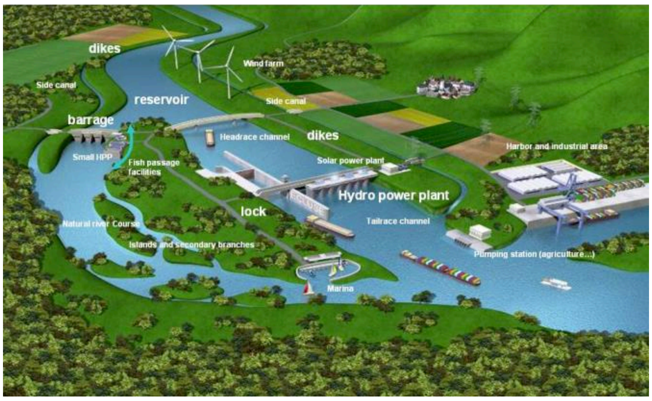

Figure 2. Typical CNR reservoir

Donzère-Mondragon has a 17 km long headrace channel, which is unusually long. Therefore, to protect dikes around channel, dedicated hydraulic structures are disposed at the entrance of the headrace channel, namely three keeping gates. These keeping gates are open in normal circumstances and must be closed gradually during floods. On the left bank, the old navigable gate (APN) consists in two 45 m wide gates and was the initial passage for boats. In the middle the new navigable gate (NPN) consists in a 60 m wide gate. Those two works are completely closed during floods. On right bank, the hydropower barrage (BGU) was designed to control water level in headrace channel during flood.

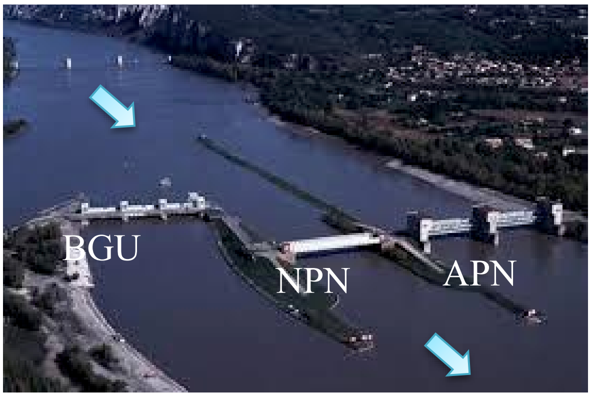

Figure 3. Keeping structures

B. Operating rules

To take in account hydroelectricity production, navigation and overflow prevention in headrace channel, operating rules are defined.

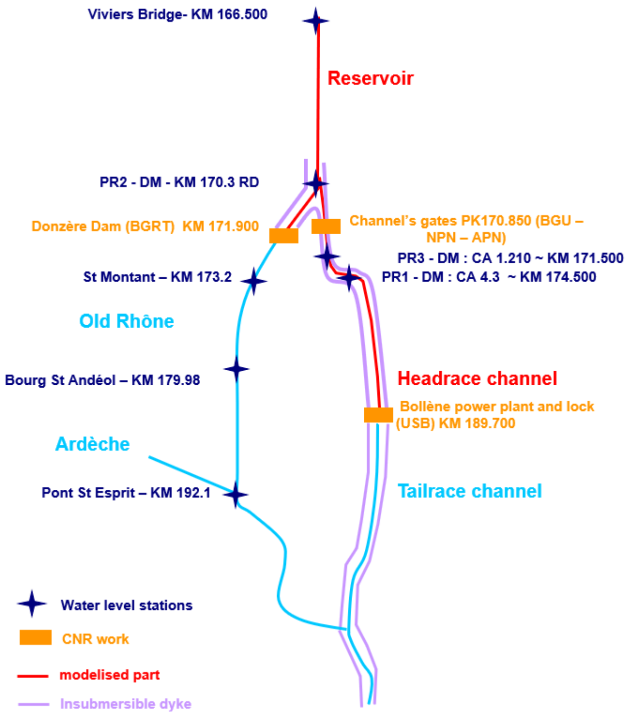

Figure 4. Donzère reach

The PID gives a prescribed flow depending on the difference between the water level at PR, Zr, and the target level, Zc. Flow regulating rules also give the distribution of the total flow between the dam and the power plant. There are three PR in Donzère. This allows us to know the reaction time of the reservoir to a manoeuvre of the dam according to the incoming flow at Viviers.

C. Mesh and model

The reach of the model extends from Viviers bridge to downstream the dam, and upstream the power plant. The mesh elements size varies from 10 m close to the hydraulic works, as instabilities may occur, to 90 m in the flood plain. The mesh is composed of about 45 000 elements and 23 000 nodes. The time step is 1s.

D. Boundary conditions

Flows at Viviers and upstream of the power plant are prescribed as well as a rating curve downstream the dam. When flow control is considered, the flow through the power plant is managed by subroutines reproducing the PID regulating rules. In this situation we prescribe only two conditions: flow in Viviers and calibration curve downstream the dam.

E. Model parameters

The aim of the study is to develop and validate the implementation of hydraulic work laws. Therefore, we primarily focus on the computation robustness rather than on the result precision disregarding the response to the model internal parameters. As a result, in this first approach of the work, we chose a uniform Strickler coefficient equals to 40 $m^{1/3}/s$ everywhere. The turbulence model is constant viscosity with an overall viscosity coefficient equals to 0.05 m^2/s.

IV. TELEMAC IMPLEMENTATION

A. TELEMAC-2D

1) Description

We represent the hydraulic works as a rectangular hole surrounded by four boundary segments. The two boundaries perpendicular to the flow have boundary conditions (usptream and downstream the hydraulic work) with prescribed flow (respectively Qam and Qav). Lateral boundaries have solid conditions.

On both sides of each hydraulic work, we define 2 control sections in the mesh (i.e. outside the hole): one upstream and the other downstream to retrieve water level and flow velocity data so as to compute respectively Ham and Hav. Additional specific sections were also defined, e.g., the regulation section, PR, to provide inlet variables (namely, the water level) to the PID flow control. Distance between the hydraulic work and the control sections was carefully chosen to reduce potential oscillations in both discharge and water level. For each work, we indicated the conveyance coefficient, Cseuil, the weir crest elevation, Zseuil, the boundaries and the corresponding control sections (see Figure 4). For the gates, we added the opening rate and the top altitude, Zsup.

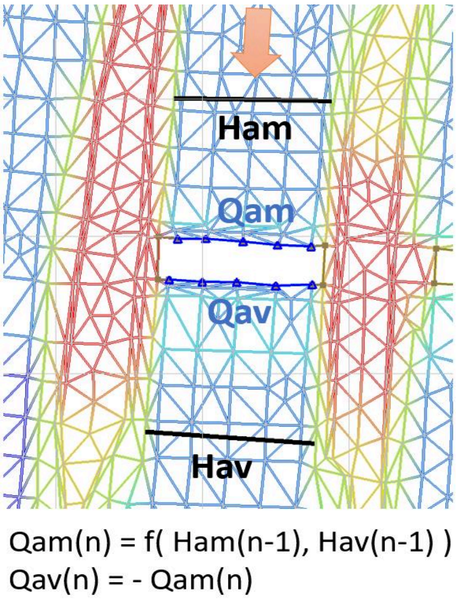

Figure 5. Representation of a work in a mesh dedicated to TELEMAC

2) Theoretical principle

Subroutines are added to TELEMAC to compute flow rate going through the hydraulic works. Computation is done according to the equations detailed in part IIC and the flow rate is updated between each time step. Three main choices are available: weir (or full open dam), gate and regulating work. Weir and gate options solve equations presented in part II C. Since flow rate is computed for step time n with n-1 hydraulics data, our solution can result in instabilities that would not exist with a non-explicit scheme.

3) Regulation detail

Weir and gate options therefore compute a flow resulting from energy conservation laws on a specific structure. This makes possible to model the structures punctually where it is needed. On the other hand, the aim of the 'regulation' option is to model the global operation of a CNR reservoir [4]. That's why, the flow calculated by this option is the total flow crossing both the dam and the plant. The distribution between the two works is computed in a second step. We need then specific laws, which give the active PR., and the target water level, Zc, for every incoming flow at Viviers and the power plant maximum flow,

For the computing part: in a first time, a PID automate derive the total flow from Zr-Zc. Then, the repartition between dam and plant is made depending on instructions. Finally, the flow rate imposed at the dam is the maximum flow rate taken among the PID flow rate and the flow rate obtained by weir laws to consider the case when dam is fully open.

4) Subroutines

We programmed subroutines for the version v8p2 of the TELEMAC system, using the USER_Q and FLUSEC subroutines to interact with TELEMAC during computation. Additionally, specifics parts of flow computation were implemented in a new module called OUVRAGES.

The flowchart in Figure 5 summarises the call sequence for the update of the imposed flow.

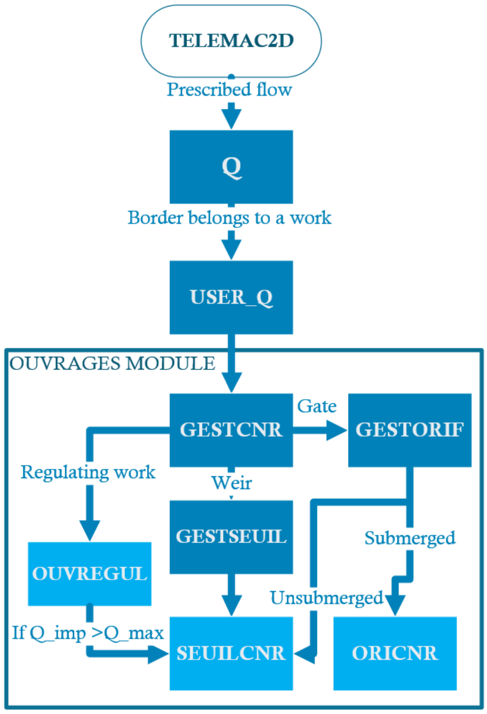

Figure 6. Flow chart

At every time step, USER_Q checks if considered boundary is from a work. If so, module OUVRAGES is called and determines the dedicated flow option (weir, gate or regulation). Then OUVRAGES subroutines call FLUSEC to get the necessary hydraulics variables and compute the prescribed flow, which is finally returned to USER_Q.

B. TELEMAC-3D

Implementation is the same in TELEMAC-3D because it computes also 2D variables which allowed us to keep the same way of computing 1D variables. Some hydraulics variables and subroutines changed of name.

The main difficulty came from the non-implementation of control section in TELEMAC-3D. Therefore, we added this option, starting from 2D subroutine.

V. SIMULATIONS

Results given here are qualitative and will be studied more precisely later. Here the main objective is to check that the procedure works properly.

A. Full open dams

In order to test weir and gate laws, a first simulation is run considering Donzère Dam and headrace channel's gates fully open. The Donzère Dam (BGRT) is modelled as a weir, and the keeping structures (BGU, APN, NPN) are always modelled as gates. In a first approach, the model is initialized with a defined water level receiving an increasing incoming flow at Viviers to reach the initial discharge of the Q1500 flood hydrogram. This first initialization, although not representing any reality, allowed us to test the limits and instabilities of our model and subroutines. The first tests did not converge and created many oscillations. It resulted that several conditions are necessary to ensure a stable computation. First, the bathymetry must not have any irregularities immediately upstream of the structure so as not to risk drying out the mesh of the upstream boundary. Second, as mentioned above, the control sections must be close to the structure. The recommended distance between the boundary section and the control section should be bigger than one mesh element. Otherwise the computation is not possible. Nevertheless, it is difficult to find the right location. There is also a risk of a wrong evaluation of the upstream and downstream flow conditions (water level and averaged velocity) with tidal flats for example. Moreover, control sections must carefully remain in the minor bed. Finally, a relaxation coefficient is introduced to filter out small frequency disturbances that can generate numerical instabilities on the weir. Despite all this, instabilities can occur during rapid changes of the flow regime and small discharges as seen on Figure 6. To avoid these, it will be necessary to establish a steady state flow over the weir.

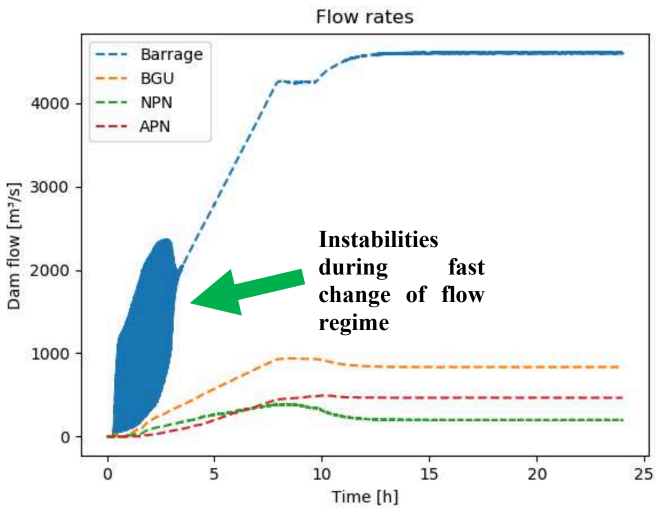

Figure 7. Flow rates into works and level error at PR during reference states

B. *Reference states*

Then regulation options were tested by simulating a succession of steady states flows over a large discharge range covering theoretical flood situations and regulatory scenarios. In those cases, the dam and powerplant (BGRT + USB) are modelled as a single regulating structure, and the keeping structures as gates. The inflow in Viviers ranges from 0 to 8000 m^3/s.

This simulation allows to visualize a realistic behaviour of the structure at every point of interest (e.g. the dam, etc…) for all of the possible configurations (low water level, normal flow, flood) and to investigate the transitory situations such as dam opening, change of PR, change of flow regime, change of plant discharge, etc.

To appreciate the results, we look at the error Zr-Zc at PR which must be kept in a given range. For out-of-range values of Zr – Zc, we focus on the necessary time it takes to the PID regulation to return to the envelope. During a PR change, we observed an error Zr-Zc = 20 cm which took around 8 hours to return into the given range. This error during PR transition can be explained by the rough model calibration and regulation rules. An improvement could be imagined to smooth the change of PR by an arithmetic mean. Finally, to avoid initialization problems (the PID flow rate depends on the previous time step), we decided to impose the input flow rate as the total outflow at first time step.

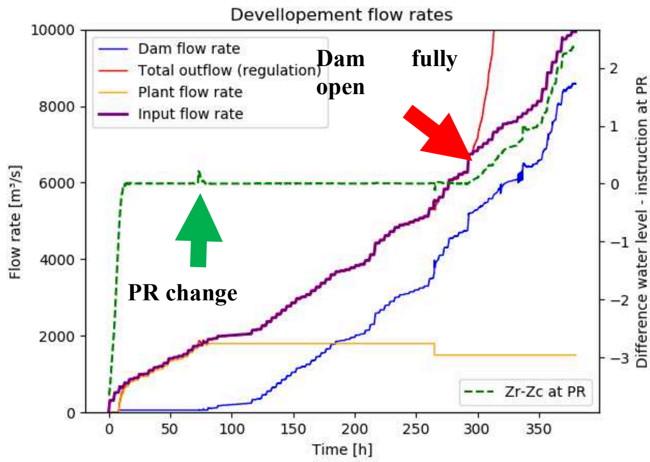

Figure 8. Flow rates into works and level error at PR during reference states

C. *Q1500*

Then the Q1500 flood is simulated in order to compare our results with a 1D model including PID regulation of the Donzère dam. The Donzère dam (BGRT) was modelled as a weir, and the keeping structures were always modelled as gates. Gates were closed progressively with the increasing input flow rate. Input flow at Viviers ranged from 6100 m^3/s to 9000 m^3/s and decreased to 6100 m^3/s. Flows through the modelled works were compared with 1D results in Table I. Few differences were observed in keeping works which can be explained by the fact that diffluences are not modelled as precisely in 1D than in 2D.

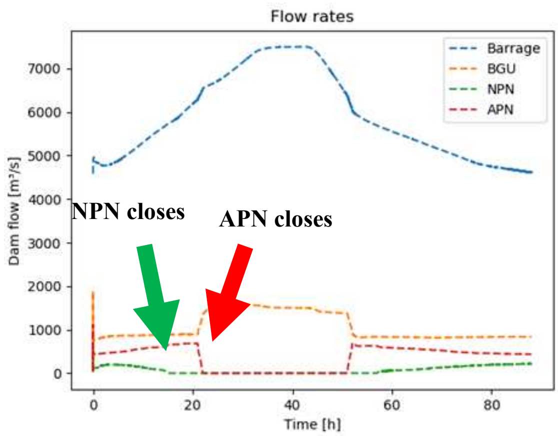

Figure 9. Flow rates through the dam and keeping gates during Q1500

Table I Flow rates at different points and time 1D and 2D results comparison

	2D Initialization flow rate (m^3/s)	**1D Initialization flow rate (m^3/s)**	**2D Flow rate at peak (m^3/s)**	**1D Flow rate at peak (m^3/s)**
BGRT	4615	4595	7490	7394
BGU	834	527	1546	1550
NPN	215	461	0	0
APN	437	512	0	0

D. Hydropower plant trigger

Finally, a hydropower plant trigger is simulated to test the robustness of the PID regulation. In this case, the dam and powerplant dam (BGRT + USB) are modelled as a control structure, and the keeping structures as gates. A hydropower plant trigger is one of the most difficult situations that can occur on a structure. It is a situation where the plant is turbine driven at its maximum flow (here 1850 m3/s). An incident stops it in emergency. The flow passing through the dam is cancelled in a few seconds, creating a large wave that flows up the headrace channel and then the reservoir. The plant can quickly allow to pass part of the flow, but the dam must then take over quickly and efficiently.

We tested the behaviour of our regulation option in this situation. The outflow from the power plant goes from 1800 m^3/s to 0 m^3/s in seven seconds. It then raises back to 855 m^3/s in a few minutes. On Figure 9 a wave of 50cm is observed at the PR. Factually, Zr-Zc reached 50 cm which takes 2h to return into the acceptable range.

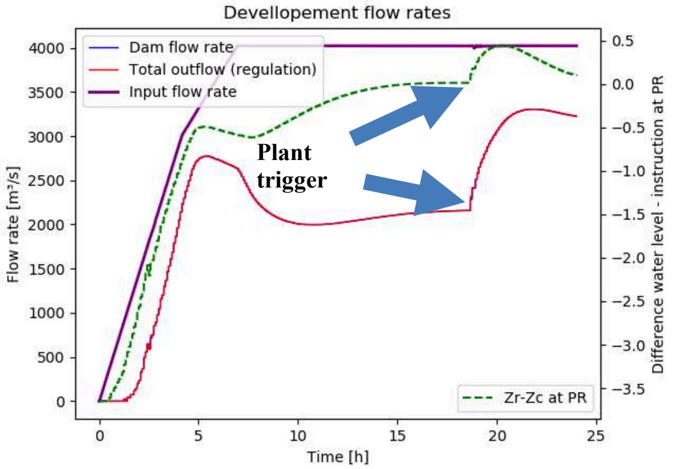

Figure 10. Dam flow rate and level error at PR during plant trigger

VI. Conclusion

A hydrodynamic model for hydraulic structures was implemented by FORTRAN subroutines on TELEMAC-2D. These sub-routines allow:

- to model precisely and easily several types of structures, without having to account for their precise geometry in the mesh
- to model the operation of the Rhône structures on a large scale with regulation

The next step is to improve the 3D version, which for the moment has only been made possible and not tested precisely. We could also test this implementation on other structures of CNR, with more complex instructions and thus develop the modularity of the subroutines.

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