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Prof. André LEJEUNE and Dr. Michel PIROTTON *

FORECASTING THE EFFECTS OF LATERAL FLOODING BASINS BY TRANSIENT SURFACE FLOWS COMPUTATIONS

Abstract

It seems possible to control and minimize the effects of extreme floods for small rivers by designing lateral basins in order to prevent the flooding of adjacent plains.

This article highlights the efficiency of this kind of hydraulic management on a river flowing through the border between Belgium and France.

The initial spreading of actual hydrographs is first reproduced in the natural topography in order to explain the observed floodings near the compound channel. Unsteady computations are carried out with a quasi-bidimensional package handling the lateral exchanges between the planned floodplains and the main river, in order to optimise the design as well as to forecast the impacts on the surroundings.

Applications assess the interest of a transient approach and the relative insensitiveness of the hydraulic parameters on the results, that points out the benefits in considering first a computational analysis. It helps to discern essential precautions aimed to ensure the best hydraulic efficiency.

1. INTRODUCTION

Throughout the ages, an intimate relationship has existed between the development of civilisations and rivers. Multiple traces of know-how in the field of hydraulic engineering inspire respect and prove the dynamism developed right from the start to approach most of the hydraulic problems we are facing today. So essential for people are benefits obtained from rivers, and so vital is the protection against floods and other river disasters.

While engineers are interested in water supply, channel design, flood control, river management, navigation improvement, it has become obvious that rivers, as a part of nature, can be mastered not by force but by understanding.

In this light, many subjects of the river hydraulics, as environment, sedimentation and erosion processes, mixed flows in compound channels are to be studied today more extensively in order to be better understood and subsequently more adequately managed. However, application of basic knowledge to practical problems requires a great deal of experience and judgement.

* University of Liège, Institut of Civil Engineering, 6 Quai Banning, B - 4000 Liège, Belgium.

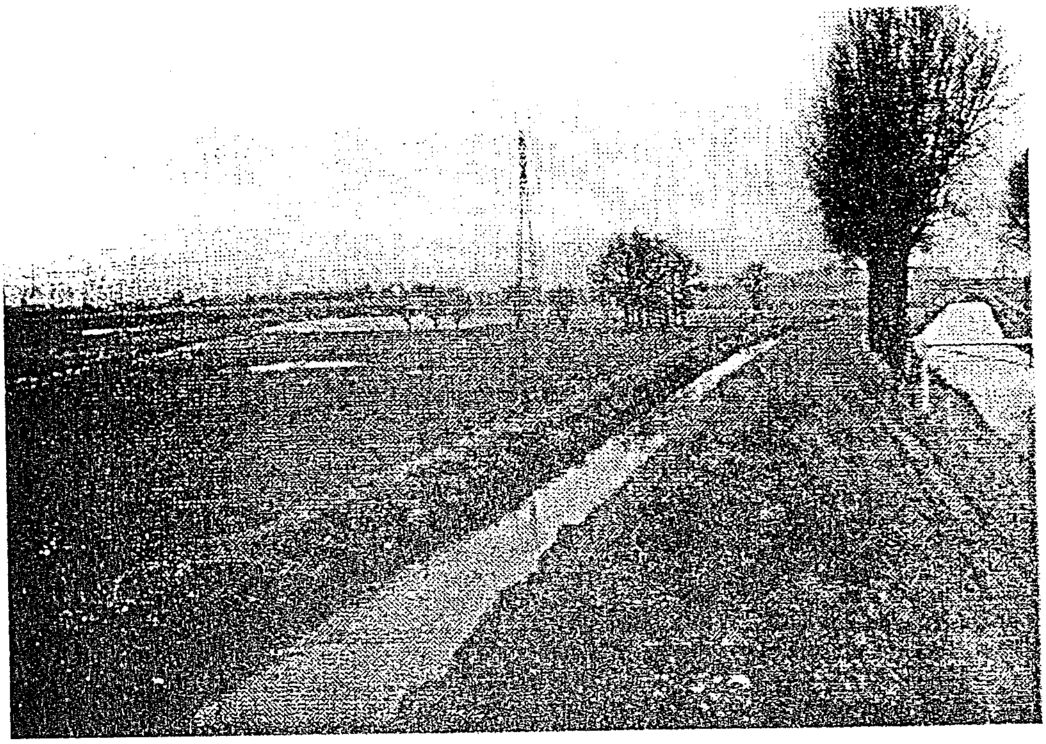

Fig. 1. - The Espierres river and the bordering canal

The general aim of this paper is to summarize the global hydraulic studies carried out in order to prevent the floodings of a small river occurring in the western part of Belgium. A first stage is devoted to reflect the actual situation in the vicinity of the river site, from the very low water level situations up to flood wave propagations. Due to natural reservoirs, the flood peak is dampened and its base extended, i.e. the flood subsides. In other words, the task was first to fit this peak reduction to the actual reality. Then, unsteady computations, handling the lateral exchanges between the planned floodplains and the main river, led to optimise the location and the size of the planned lateral reservoirs as well as to forecast their impacts on the surroundings.

2. DESCRIPTION OF THE STUDIED SITE

« L'Espierres » is a small river flowing through the frontier between France and Belgium at Estaimpuis. This tributary is parralel to a navigable waterway for small ships along 8 kilometres before joining the Escaut river. Because of the significant difference of water quality, mixing is not permitted between both flows.

When floods occur in the Espierres river, converging rainfalls of a 5,000 ha catchment located mainly in France, the resulting flood stage implies a complete cross-section filling. Gradually, water spreads on the flood plains and flows into the bordering canal.

Two basins were planned in Belgium in order to protect the near by sites of the river. The simulations have to reflect the ability of the lateral weirs to diverge the prescribed volumes and to forecast the smoothing of the hydrograph propagating in this 8 km long section.

3. GENERAL CONSIDERATIONS

If we focus on the thin water layer propagating on natural catchment slopes resulting from a significant rainfall, we can compute the ensuing hydrograph that propagates in the main drainage path. This specific software is theoretically and numerically described in other communications (see [1]). The temporal evolution of the upstream imposed discharge is illustrated on figure 2.

This figure shows a peak discharge of 54 m3/s that has been referenced in a preview analysis. This common approach consists in handling the problem in a steady way. This discharge is assumed to be reached anywhere when maximum water levels are measured at different sites. We attempt to search uniform values of friction factors leading to a reasonable agreement between computed water profiles and measured values.

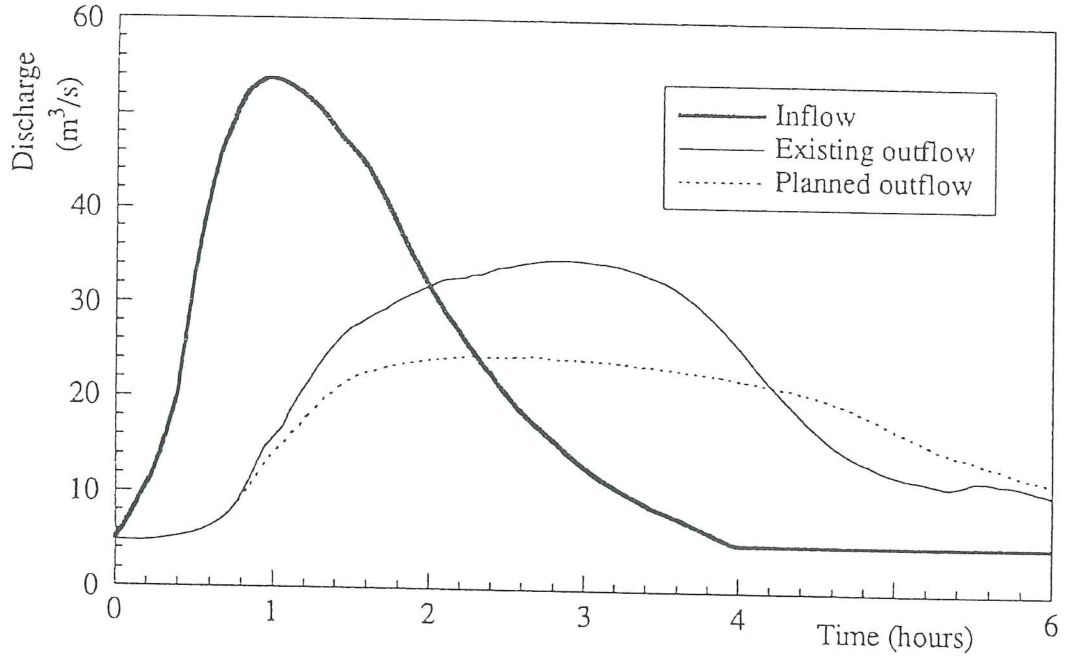

Fig. 2. - Flood subsidence between the entrance and the outlet of the studied section

This sequence produces unrealistic values even though the river path is straight and the main channel very smooth due to a partial concrete revetment. This experiment suggests two major remarks. Firstly, local overflowings are so important that corresponding cross-sections cannot be handled as uniform ones. We have to face the understanding of the flow in compound channels, the importance of which is indicated by the number of investigations that have been reported in the last few years.

Secondly, the computed inflow can be locally overestimated. Since the global balance suggested by the hydrological approach remains accurate, we deduce that it is essential to account transient influences that smooth the hydrograph along its propagation. The smoothing would not result from the roughness properties of the river but much more from the exchanges between the main path and lateral areas.

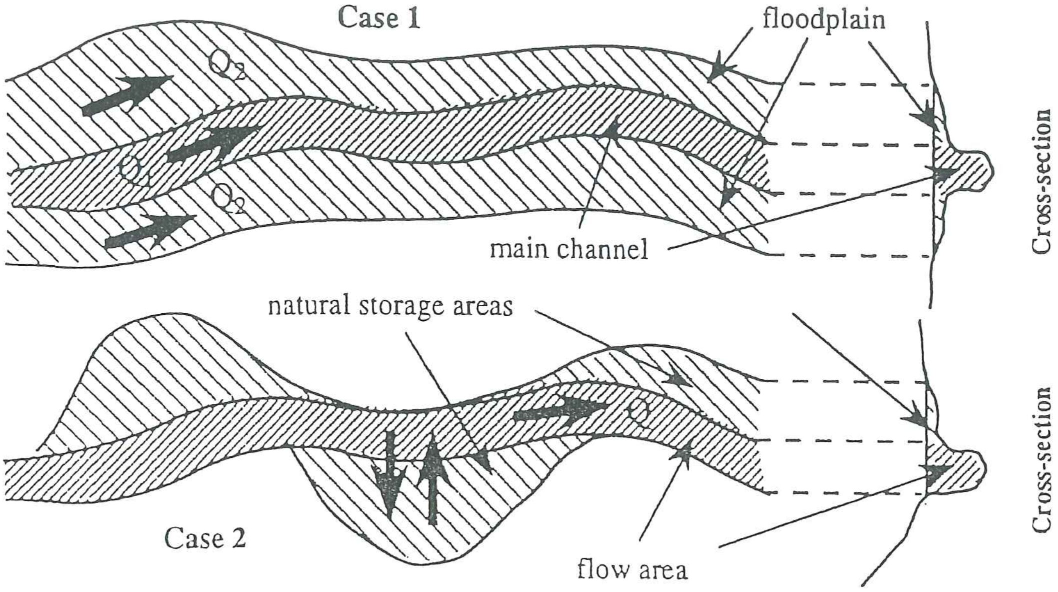

Fig. 3. - Hydraulic influences between the main channel and the floodplain

The sketches on the figure 3 highlight two potential circumstances that affect the suitable reasoning to achieve about lateral exchanges.

In the first case, the typical shape of the cross-section on the whole is spatially uniform enough to conceive that each sub-section is hydraulically homogeneous, inducing two main streams. Because of the very great velocity gradients reflecting large speeds in the main deep channel compared with those of the shallow floodplains, momentum transfers occur through the imaginary interface between both sub-sections. All these effects explain why common methods based on conveyance considerations can lead to substantial errors, as well as why the right approach has so far to be found.

In the second event, the open water course is locally disturbed, especially on the floodplain, by topographic unevenness and manmade structures. All these hazards prevent the discharge to develop freely on the floodplain. It acts as lateral storage areas, with hydaulic death zones where water movements occur only in the transverse direction.

The occurrence of culverts in the Espierres river in order to flow beyond embankment fills for highways or railways and the variable height of river banks imply that this last event has to be preferred.

4. THEORETICAL AND NUMERICAL CONSIDERATIONS FOR OPEN-CHANNEL FLOW

The spreading of lateral hydrographs computed by suitable hydrological codes can be achieved with unidimensional computations of unsteady free surface flows induced in nets of natural rivers. Thus can be followed and explained the whole story of a flood formation, from the thin stream of water rushing down the hillside to the temporal and spatial evolution of water depth and river flow threatening riverside residents. This kind of approach was performed to obtain the upstream imposed hydrograph illustrated on figure 2.

However, the main assumptions that lead to the set of equations (1) do not prevent the software from helping to manage water resources of complex networks submitted to variable conditions. Therefore, it can reproduce all transient flows occurring in nets of rivers resulting from transient lateral exchanges with flood plains through a suitable statement of the term q_L.

$$\frac{\partial}{\partial t}\begin{bmatrix}\omega\\ q\end{bmatrix}+\begin{bmatrix}0 & 1\\ (c^2-\rho_\omega u^2) & 2\rho_\omega u\end{bmatrix}\frac{\partial}{\partial x}\begin{bmatrix}\omega\\ q\end{bmatrix}+\begin{bmatrix}-q_L\\ g\omega\left.\frac{\partial Z}{\partial x}\right|_\Omega+F+2\frac{\partial}{\partial x}\left(\nu\omega\frac{\partial u}{\partial x}\right)\end{bmatrix}=0$$

$$\equiv\frac{\partial X}{\partial t}+\frac{\partial B(X)}{\partial x}+D(X)=0 \qquad (1)$$

with

F	:	the friction term
ω	:	the wet cross-section
u, q	:	the average speed and the average flow in the section
q_L	:	the lateral inflow or outflow
Z	:	the elevation of free surface
ν	:	the kinematic viscosity
ρ_ω	:	the parameter of uneven distribution of the axial speed in the section

The coexistence of several flow rates with shocks and bores in ramified nets of variable cross section arms requires the development of suitable capturing methods. They have to simulate sharp transitions without excessive smearing on several meshes or excessive growing of dissipative processes.

The Mac-Cormack scheme belongs to the class of explicit finite difference methods. Its fractional step approach makes it second order accurate in time and space and brings some selective dissipation in the system. This shock capturing technique performs reliable simulations of unsteady appearances, movement and disappearances of sharp transitions correctly situated in the most various conditions of hydraulics.

$$X_i^{'}=X_i^n-\frac{\Delta t}{\Delta x}\left[(1-\alpha)A_{i+1}^n-(1-2\alpha)A_i^n-\alpha A_{i-1}^n\right]-\Delta t D_i^n$$

$$X_i^{n+1}=\frac{1}{2}\left(X_i^{'}+X_i^n\right)-\frac{\Delta t}{2\Delta x}\left[(1-\beta)A_{i+1}^{'}-(1-2\beta)A_i^{'}-\beta A_{i-1}^{'}\right]-\frac{\Delta t}{2}D_i^{'} \qquad (2)$$

The predictor-corrector sequence written in (2) implies to choose (0,1) for (α,β) together with a permutation of both values at each time step.

Furthermore, gaining from the whole experience of finite element packages, the knowledge of factors affecting the intrinsic behaviours of the discretisations was devoted to introduce a slight modification of this well-known scheme [2]. In particular, Katopodes suggests to use discontinuous weighting functions in the finite element approach that take the flow conditions themselves into account.

In accordance with this work, some dissipative terms were appended in order to strengthen the initial shock capturing capabilities of the original scheme.

The accuracy of the code in tracking and predicting subcritical and supercritical flows to numerically coexist at any moment in different locations of the discretisation was verified in the worst conditions induced by dam-break flood-wave simulations and jumps propagations.

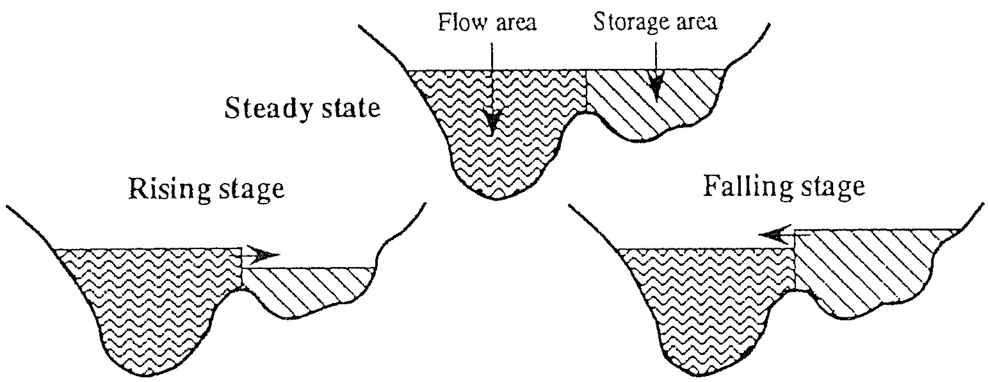

Fig. 4. - Illustration of the transient exchanges

Concerning the reservoir flood routing, only storage phenomena are considered. The influence of impulsive motion of the inflow is neglected and with the assumption of a horizontal water surface, the storage effects are quickly transmitted.

As illustrated on figure 4, the interface between both sub-sections acts as an imaginary solid sharp wall. Thus, we extend the available stage-discharge curve of lateral diversion weirs to this situation with an efficiency factor to be fitted.

Besides, the numerical code takes into account backwater effects of the different culverts. The flow within each barrel can have a free surface with subcritical or supercritical conditions depending on roughness and transient upstream and downstream water levels of the culvert. When the upstream head is sufficiently large, the flow may fill the barrel which induces pressure surge computations.

Simulations are carried out using real digitised cross-sections of the stream channel and the floodplain.

5. RESULTS FOR THE EXISTING SITUATION

The computation is performed using a fairly constant 50 m spatial mesh. Because properties are assumed to be uniform, only two informations have to be provided, one about morphological properties of the channel and another one to characterise lateral exchanges.

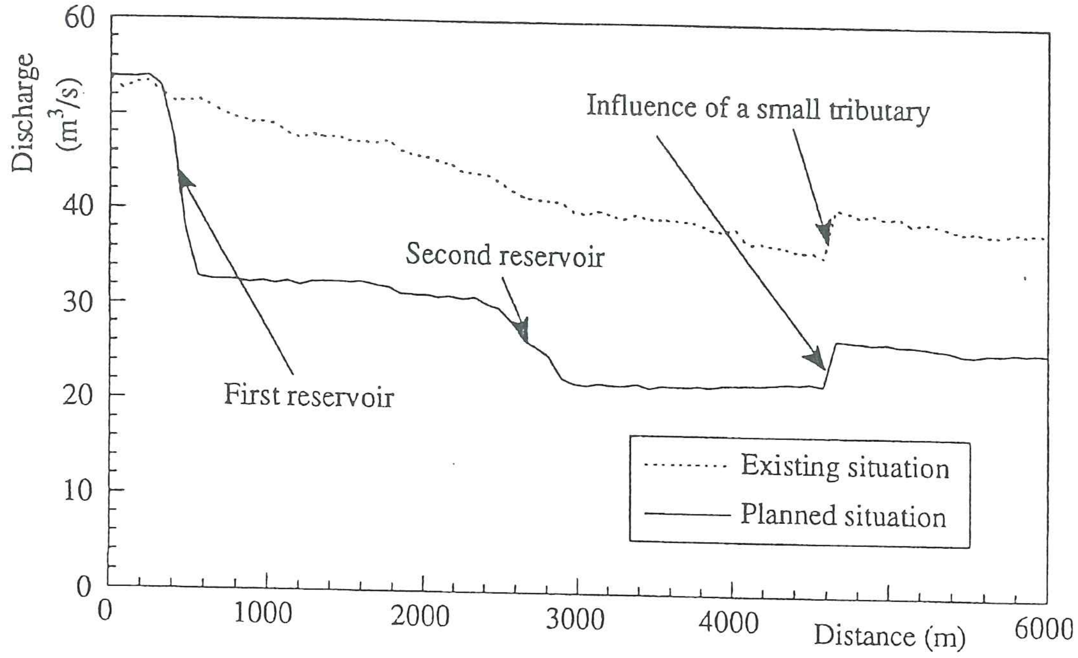

Fig. 5. - Maximum discharge at each cross-section

An excellent fit between computed values and gauged data was obtained with a physical relevant roughness coefficient that corresponds to referenced values for the same conditions. Figure 5 shows a significant smoothing of discharge along the propagation, due to the natural storage in the surrounding fields. Figure 6 confirms the location of the observed overflows.

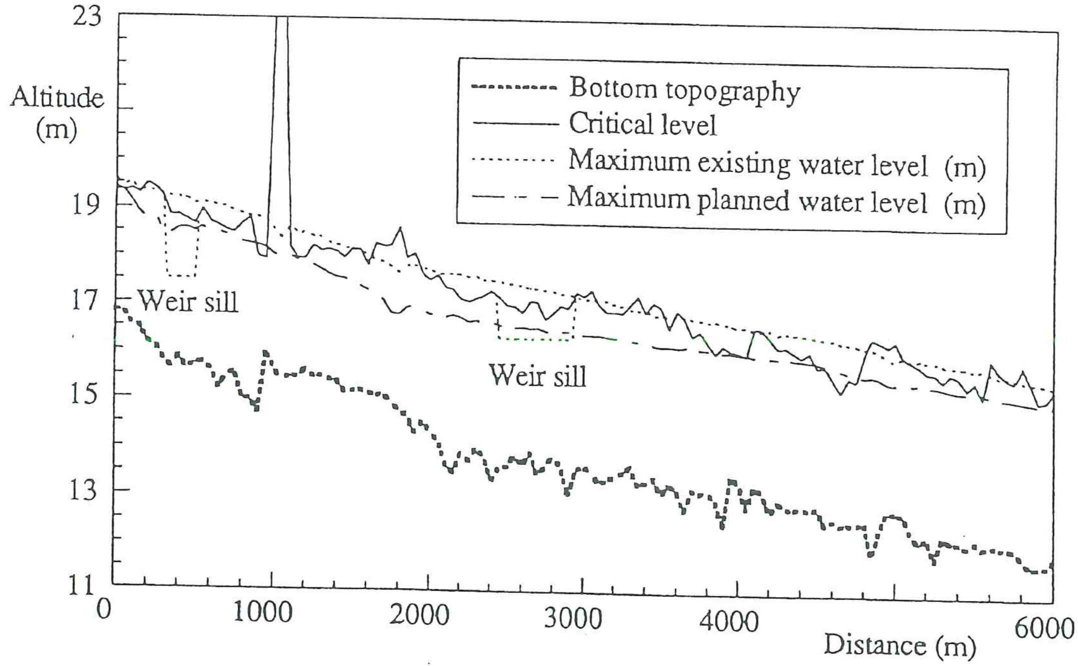

Fig. 6. - Maximum water level at each cross-section

6. IMPROVEMENTS OF THE PLANNED SITUATION

After many computations, reservoirs were designed to lie on a respective maximum area of 6 ha and 11 ha. The figure 6 shows the location of the basins and the planned lowering of the maximum water profile. The weir sill is 200 m long for the first basin and 500 m long for the second one. In order to maintain wetted areas behind the weirs, we suggested a slight difference of level between the bottom of the reservoirs and the sills, as illustrated on figure 11. The delayed emptying of these water layers is regulated by gates.

The prospected effect is completely fulfilled with the aid of a small dike at the confluence with a tributary that induces a preliminar discharge peak. This last one propagates upstream and downstream in the main path, as highlighted in figure 5.

We observe a first significant smoothing from 55 m^3/s to 33 m^3/s and a second stair up to 22 m^3/s. This figure confirms that the sole roughness of the main channel cannot induce any subsidience of the flood during its propagation. We see indeed that no lowering occurs between both reservoirs where the flow is maintained in the main channel.

Figure 7 shows the fundamental difference of results between a steady analysis and transients computations. The prospected modifications bring no significative modifications upstream of the reservoirs. The level of the section 1 depends mainly of the hydrograph which has to pass through this wetted area, with minor influences of downstream conditions.

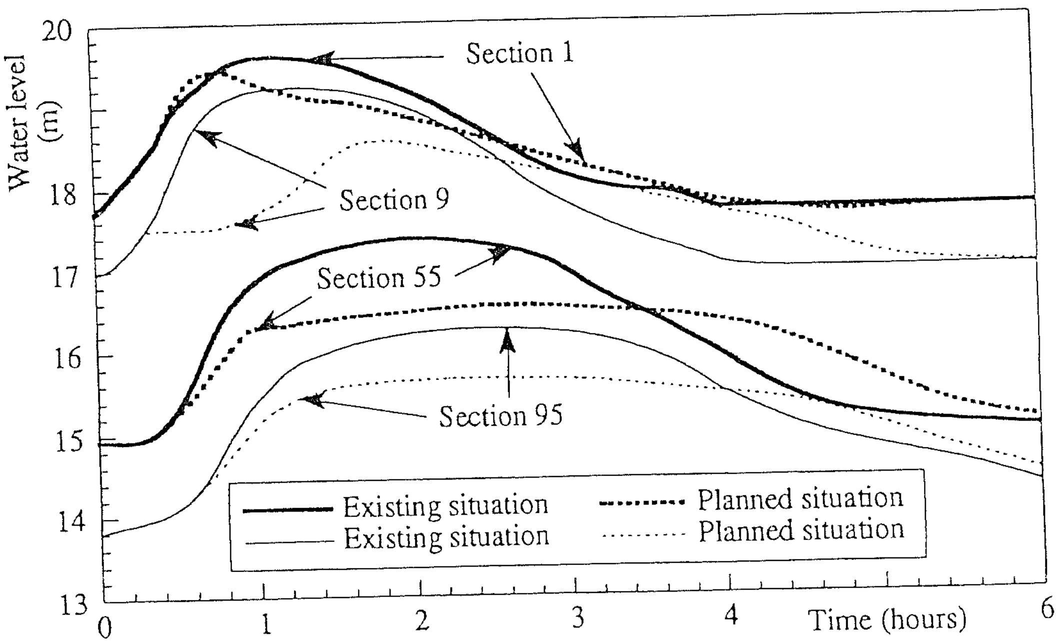

Fig. 7. - Temporal evolution of free surface at different sections

Figures 8 and 9 explain the gradual work of the fisrt weir. A comparison between the two figures reveals that the weir begin to act from 16 m^3/s. Then we observe a constant level during the filling of the first layer behind the embankment.

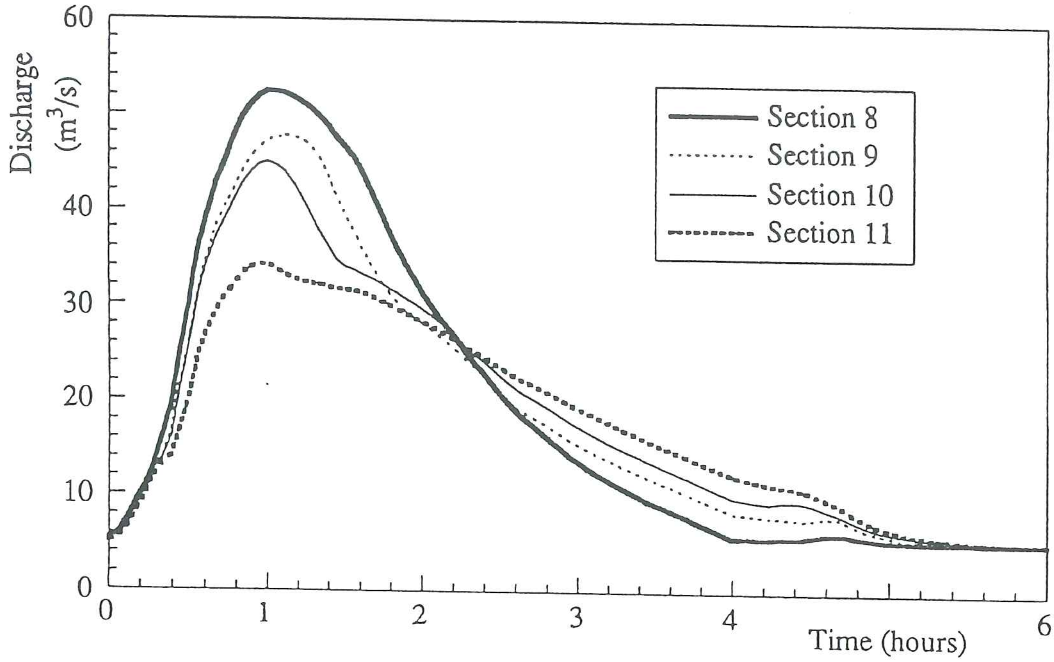

Fig. 8. - Temporal evolution of discharge along the upstream weir

Computations assessed that discrepancies of the efficiency factor for this kind of diversion had minor effects on the global exchange balance, due to the characteristic time of the hydrograph. A middle value was selected in accordance with the works of Carlier [3] or Sinniger et al [4] for classical lateral thin crested weirs.

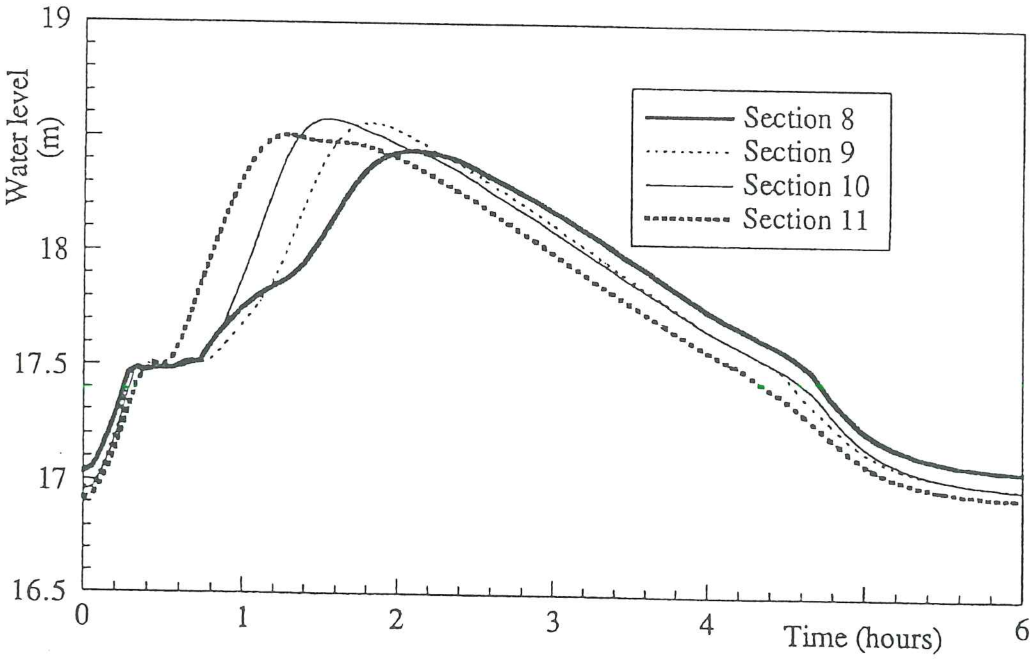

Fig. 9. - Temporal evolution of free surface along the upstream weir

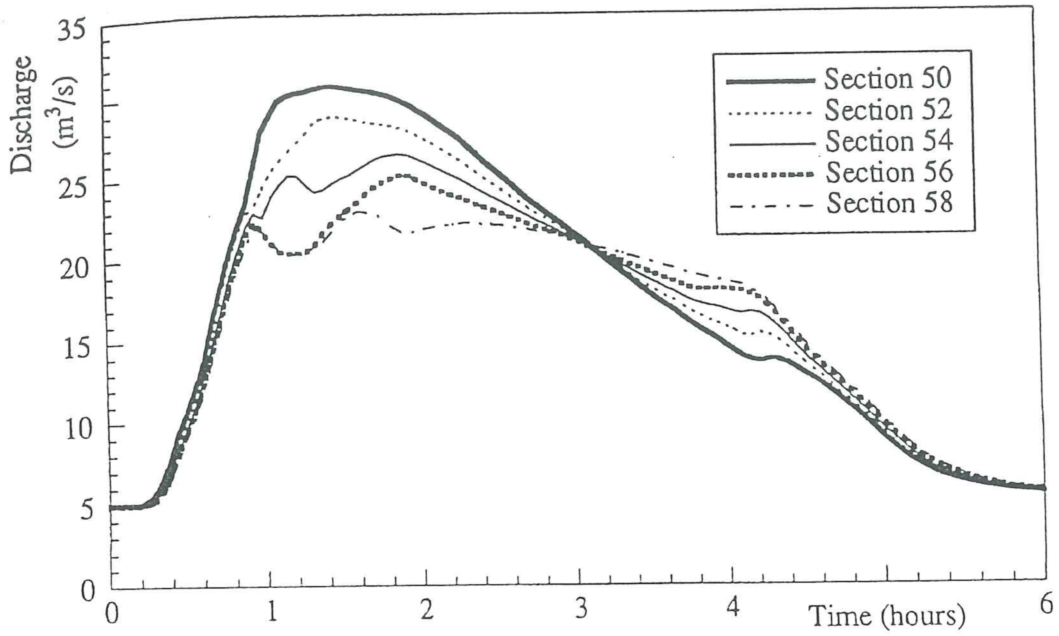

Fig. 10. - Temporal evolution of discharge along the downstream weir

Figure 9 highlights that the downstream part of the first weir is more efficient. This is not surprising since the water height lowers first along the exchange area, restraining the lateral discharges. Then, the water profile has to increase continuously in order to join downstream the level of the main path flow, producing more lateral exchanges.

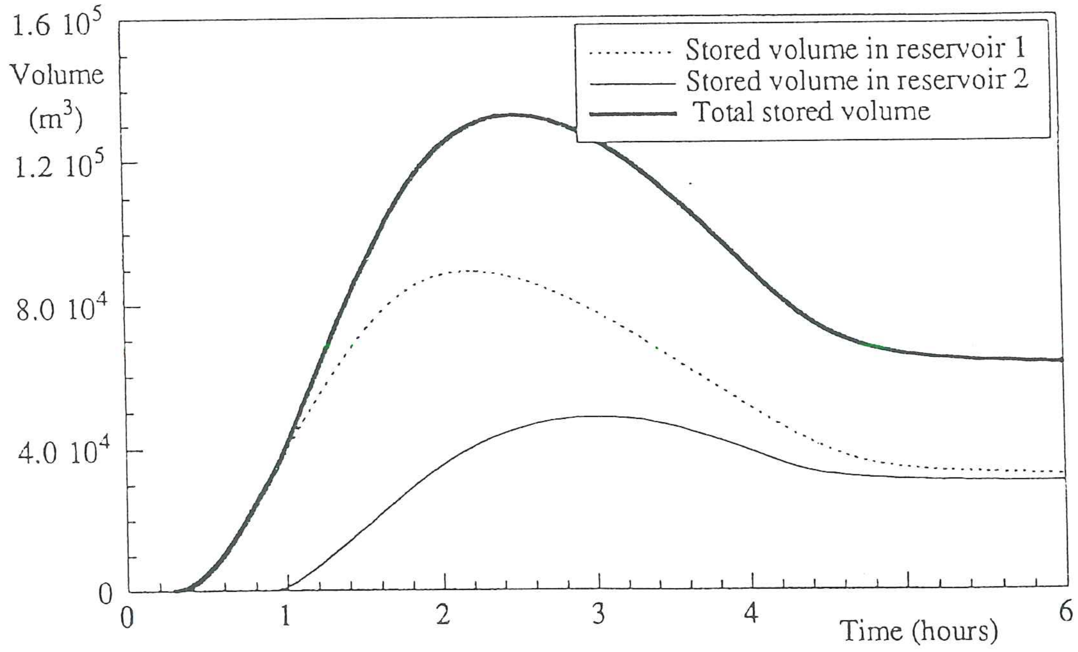

Fig. 11. - Temporal evolution of stored volume in both reservoirs

Figure 8, as well as figure 10, proves that the initial hydrograph is completely altered along each weir. The storage capabilities of the second basin are overestimated in the actual context. But it will have to handle with morphological changes on the present catchment and to converge rainfalls of extended area during future flood events. The last figure shows the whole history of the storage and exhibits the time lag between the maximum peak in both reservoirs.

7. CONCLUSION

This article proved that steady considerations are inadequate to reproduce current floodings situations. In order to ensure a fit design and an adequate management, they have to evolve towards transient computations that reflect the gradual lowering of the discharge peak. In several actual cases, this smoothing of the initial hydrograph can be mainly explained by lateral exchanges between the main channel and the floodplain.

We showed that natural as well as manmade obstacles prevent in practice a secondary flood to freely develop on floodplains. A first approach consists in considering these areas as death zones. They maintain their water level by lateral exchanges which imply only transverse discharges. This application assessed that they are correctly modelized by lateral weirs laws since the dynamics of these diverted flows can be neglected.

The code was applied successfully to an small belgian river. It accurately reproduced the overflowing of the actual flood wave propagation resulting from significant rainfall events on the catchment. With the assurance of reliable simulations gained by comparison with gauged measurements, computations were then devoted to forecast the lowering of the water profile after the buildings of flooding basins in order to set up an economical design.

Besides, this paper pointed out the benefits in considering first common physical features of the flows, then in discerning theoretical and numerical shortcomings aimed to ensure the best numerical efficiency.

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