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# Modeling Pressurized Flow through Hydraulic Structures and Bridges Using a 2D-SWE-based Model

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## Abstract

Two-dimensional (2D) hydraulic models solve the Shallow Water Equations (SWE) for the simulation of free surface flows. The necessity of considering in the calculations specific hydraulic structures, such as bridges, gates, weirs, culverts, etc., for representing more realistic flood scenarios, imply the integration in the 2D-SWE of empirical equations that represent the flow through these structures. These empirical equations are usually implemented as internal conditions over a 1D line, modifying the equations with which the flow is calculated in the edges of the mesh elements located at both sides of the line. This approach can be good enough for representing the hydraulic behavior in general. However, this 1D condition over a line, which only affects the element edges, is not a good approximation for simulating the hydrodynamics of pressurized flows, as it is the case of very wide bridges and lids over channelized rivers. New modelling strategies for simulating pressurized flows using the 2D-SWE, the Two-Component Pressure Approach method (TPA) and the Preissmann Slot Method (PSM), have been implemented in Iber. Both approaches were tested in a coverage of a channeled river characterized by several abrupt curvature changes and a contraction/expansion of their wide, and in a bridge located in a river reach that obstructs most of the floodplain. The TPA and PSM methods presented good numerical approaches for simulating pressurized flow for 2D-SWE-based models, fine-tuning the hydraulic behavior, and representing the most critical regions when a pressurized flow is generated in hydraulic structures.

**Keywords:** Pressurized flow; 2D-SWE; Two-Component-Pressure Approach; Preissmann Slot Method; Hydraulic structures

## 1. INTRODUCTION

During a flood event, the occurrence of pressurized flows at certain locations is quite common due to the reduction of the effective section by hydraulic structures such as bridges, underground river reaches or channeling rivers in urban areas (Sopelana et al., 2018, 2017), but also induced by the accumulation of vegetation and large wood on it (Ruiz-Villanueva et al., 2013; Ruiz Villanueva et al., 2015). The numerical modeling of the flood at these locations using two-dimensional Sallow Water-based models (2D-SWE) is no longer valid unless the equations are modified to take into account the vertical confinement of the flow (Cea and López-Núñez, 2021).

The effect of the bridge deck in the hydrodynamics is generally modeled with empirical one-dimensional (1D) discharge equations that relate the head loss to the water discharge through the bridge (Bladé et al., 2014a, 2014b; Costabile et al., 2015). Numerically, the deck is implemented as a thin line, its width in the flow direction being neglected. Since the bridge discharge equations, developed assuming steady flow conditions when the flow is mostly 1D, they are not valid when the flow pattern is clearly 2D or perpendicular to the bridge deck, and unsteady flow is produced.

Several approaches have been proposed to modify the original 1D-SWE for simulating pressurized conditions (Aureli et al., 2015), and later on extended to 2D-SWE. On one hand, the Preissmann Slot Method (PSM) is a classic approach, initially developed for 1D conduits (Preissmann, 1961), that consists of adding a hypothetical, indefinitely extended slot to the crown of the conduit (Bousso et al., 2013; Kerger et al., 2011) to simulate an artificial free surface. The width of the slot is the numerical parameter of the method. In practice, the Preissmann slot width is set as a percentage of the pipe or channel width, and it is not necessarily related to any physical property of the conduit (Cea and López-Núñez, 2021). This method has been extended to a two dimensions and applied in few numerical models (Aragón-Hernández and Bladé, 2017; Bladé et al., 2019; Maranzoni et al., 2015) by considering a cross-shaped slot in an surface element (Figure 1a).

 

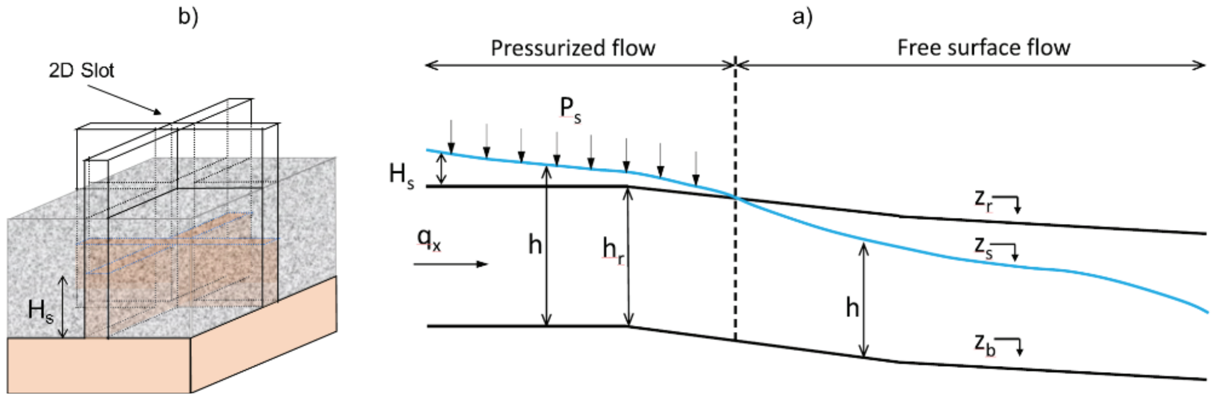


**Figure 1**. Representation of the extension of the Preissmann slot to a 2D surface element (a) and scheme of mixed flow conditions including a region under pressure and a region under free surface (b).

On the other hand, Two-Component Pressure Approach (TPA) (Vasconcelos et al., 2006) overcomes the problem of the artificial free surface flow regeneration of PSM by considering the total pressure as the sum of two components: a hydrostatic pressure and a dynamic pressure. This method assumes certain elasticity of the conduit and neglects the compressibility of water. Extended from the water hammer equations for 1D pipes, the conduit elasticity is related to the wave celerity in 2D under pressurized conditions, which is the numerical parameter of the method (Cea and López-Núñez, 2021; Fraga et al., 2017; Sanders and Bradford, 2011; Vasconcelos et al., 2006).

In practice, both PSM and TPA methods add an artificial pressure term ($P_s$), being zero in regions where the water surface elevation ($z_s = z_b + h$) is lower than the roof elevation ($z_r$), and positive in regions where the water depth is constrained by the roof (Figure 1b). This term is calculated throughout the previous methodologies: with the slot width percentage ($T_s$) in PSM; and with the stiffness constant ($K_s$) in TPA.

This paper conducts a comparison between PSM and TPA methods when pressurized conditions are produced, besides analyzing the two numerical strategies for modelling bridges: classical 1D approach where the bridge is defined as a line and considering the generation of pressurized conditions under the bridge span. To that end, we analyze the hydraulic behavior of a channeled river that a reach is planned to cover and of a specific case of a bridge non-alignment with the flow direction that potentially generate pressurized condition under its spans. Both methods works similarly, presenting good numerical approaches for simulating pressurized flow for 2D-SWE-based models, fine-tuning the general hydraulic behavior of the lidded areas, and representing the most critical regions when a pressurized flow is generated in hydraulic structures.

## 2. CASE STUDIES

The previous numerical strategies to simulate pressurized flow and bridges were tested in two real study cases. Case Study 1 is the coverage of a channeled river characterized by several abrupt curvature changes and a contraction/expansion of their wide. The limited hydraulic capacity of the channeling, besides the cross-waves generated by the changes on the channel direction and width, produces pressurized flow conditions. On the other hand, Case Study 2 consists of a bridge located in a river reach that obstructs most of the floodplain. The discharge capacity of the bridge is conditioned by the bridge abutment and a relatively small culvert located under this abutment. The location and geometry of the bridge, besides its limited hydraulic capacity during extreme flow scenarios, generate a partial pressurized flow at its upstream part. In both cases, the slot width percentage and the stiffness constant were $T_s$ = 10 % and $K_s$ = 50 m/s$^2$, respectively.

### 2.1. Case Study 1: coverage of a channeling river

Case Study 1 analyses the hydraulic behavior of the last reach of Capaspre Creek, a channeled stream that crosses the coastal village of Calella (Spain). In the recent years, recurrent flood events pushed the authorities to cover the creek in all the urban area. These works were split in two areas, being currently executed only the part corresponding to the downstream (Figure 2a). A first analysis was carried out to determine the areas where pressurized flow would potentially be produced. These results are compared with a second analysis performed considering the coverage of the river with a lid of 3 m of height and the two numerical approaches: PSM and TPA.

The river comes down to the village and runs through it by means of a channeling completely disconnected of the floodplains (Figure 2b) because the riverbed is below of the adjacent topography (Figure 2c). This stream has around 340 m of length, a mean slope of 2.25 %, two changes of direction, and a contraction/expansion of areas. The upper part is characterized by a rectangular cross-section of 7 m-width (245.25 m). Then the channeling is abruptly widened by means of two ramps (42.25 m) maintaining the shape of the central part (Figure 2c). During the next 27 m the stream is gradually narrowed, passing from 15.5 m to 7.5 m, which is maintained until the end of the section that is already covered.

The hydraulic conditions were a constant discharge of 173.6 $m^3/s$ as an inlet, critical regime as an outlet and a roughness coefficient of 0.02 $m \cdot s^{-1/3}$ for the bottom and the walls. The stream was covered by a lid keeping a free height of 3 m for the whole channeling, except the ramps area where a constant elevation of 13.3 m was implemented as the lower part of the lid. The study area was discretized by means a calculation mesh of triangular and quadrilateral elements aiming to define the pressurized area accurately. Three different ratios were used: 13904, 56181 and 66335 els./ha; both an order of magnitude above the common ratios used for hydraulic studies (Sanz-Ramos et al., 2020).

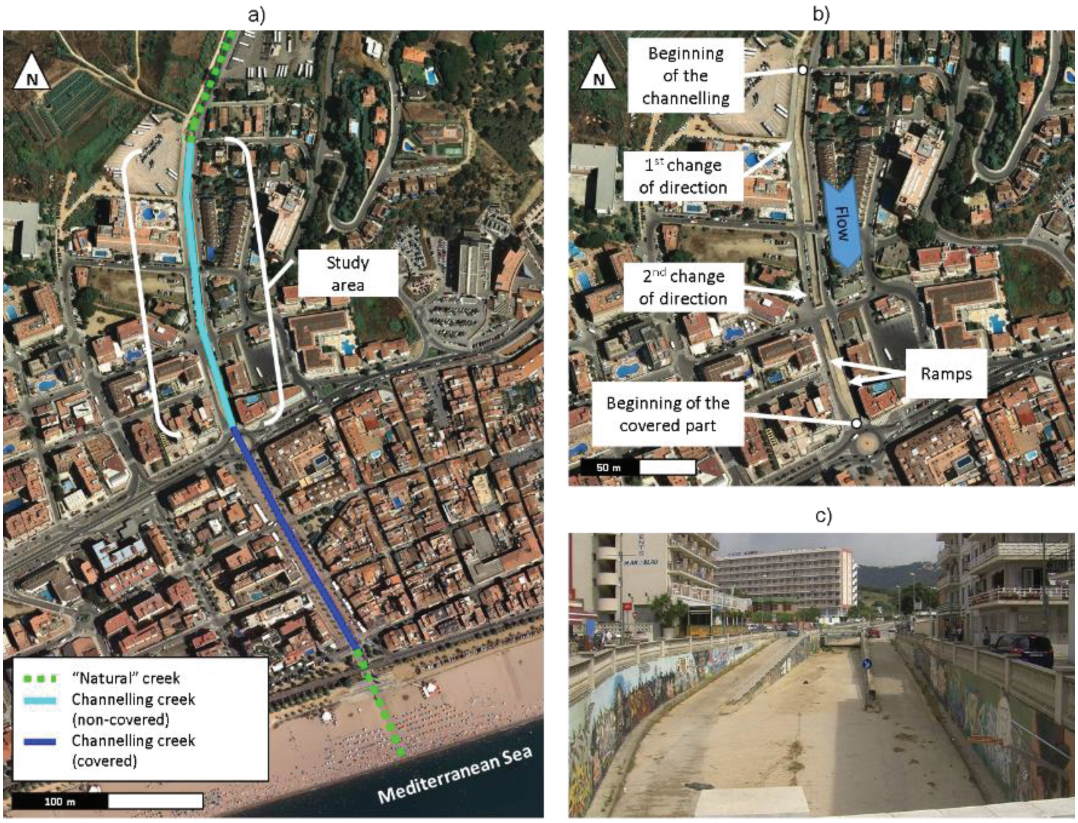


**Figure 2**. Case Study 1. (a) Sketch of the different parts of the Capaspre Creek (lowest stream). (b) Particularities of the analyzed stream (background image from (ICGC, 2021), licensed under Creative Commons Attribution 4.0 International (CC-BY 4.0)). (c) Image of the two ramps taken from the covered section to upstream (source: www.radiocalella.cat).

### 2.2. Case Study 2: bridges as lids

Case Study 2 consists on the analysis of a flood scenario in the village of Sarria (Spain). The river crosses the urban area and two bridges allows the traffic between both river sides (Figure 3a). The hydraulic behavior of the downstream bridge was analyzed considering the flow through the bridge by means of two approaches: the deck is modeled as a thin line in the numerical mesh; and the whole bridge is modeled as a lid. In the first case, the width of the bridge in the flow direction is neglected, whereas in the second one is fully considered.

The study area is about 785 m-long and a mean width of 260 m. The bridge and culvert (Figure 3b) were implemented numerically in the model. Despite the culvert can also be considered as a lid, in this case the flow through it was approximated with an algebraic equations based on Manning's formula. A hydrograph with a peak discharge of about 375 $m^3/s$ was imposed as inlet condition. The area was discretized by means of an unstructured mesh of triangles with a ratio of almost 30000 els./ha, with smaller elements in the area of the bridge.

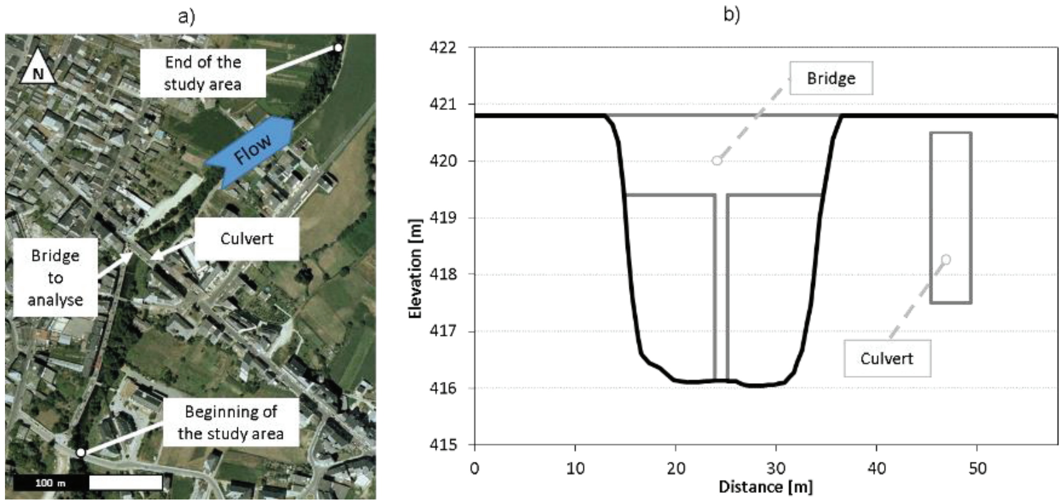


**Figure 3**. Case Study 2. (a) Sketch of the different parts of the study area of Sarria (background image from (IGN, 2021), licensed under Creative Commons Attribution 4.0 International (CC-BY 4.0)). (b) Dimensions of the bridge and culvert.

## 3. RESULTS

### 3.1. Case Study 1

The results of the hydraulic behavior of the pre-coverage channeling model shows that first the reach of the stream, and a small area at the outer side of the 2nd change of direction (Figure 2b), overtops 3 m of depth (Figure 4a). Thus, this areas can potentially be pressurized when the lid is considered. These areas were fine-tuned with higher mesh ratios: 56181 els./ha (Figure 4a2) and 66335 els./ha (Figure 4a3). A better representation of the cross-waves generated downstream of each change of direction is produced and, thus, the presence of new potential pressurized areas is enlarged.

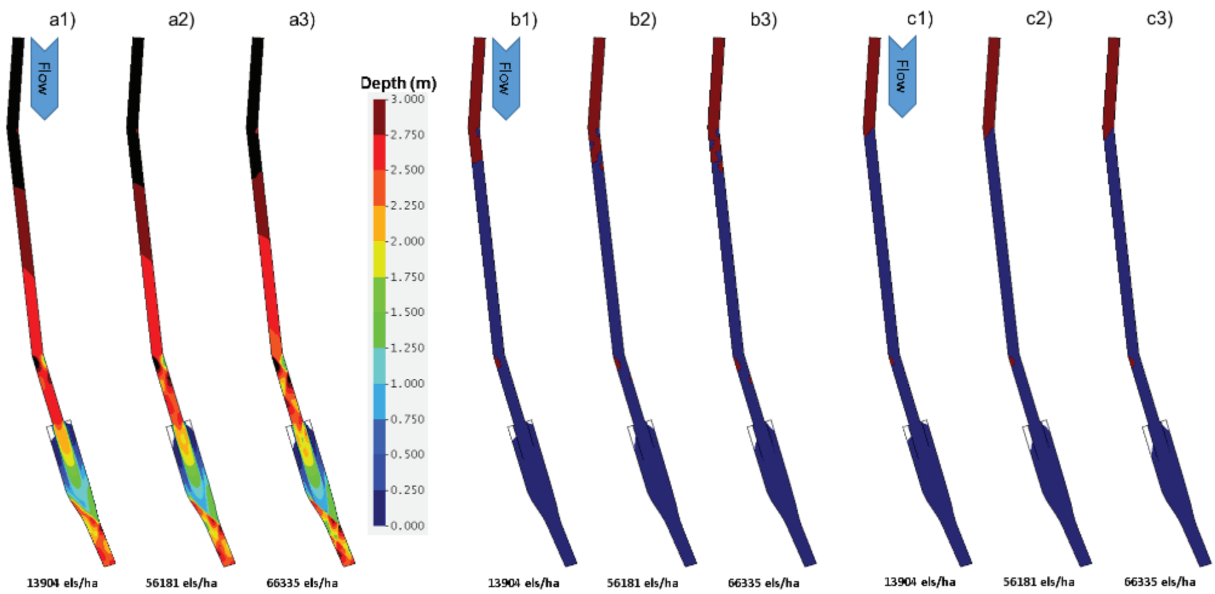


**Figure 4**. (a) Maps of depth of the pre-coverage channeling where potential pressurized flow areas are colored in black. Maps of free surface (blue) and pressurized (garnet) areas for PSM (b) and TPA (c) methods.

The pressurized areas were well-captured by PSM (Figure 4b) and TPA (Figure 4c) methods. These areas slightly differs from the areas where pressurized flow would be produced in the pre-coverage model (Figure 4a, water depths > 3 m are colored in black) because a flow acceleration was produced due to the reduction of the free area. This acceleration was greater for TPA (Figure 5a1) than for PSM (Figure 5a2), generating less extend of the pressurized area because the whole channel was in supercritical regime, and the perturbation propagates to downstream with faster velocity. Despite the presence of cross-waves under the lidded area in both cases, TPA approach presented only a pressurized area at the outer side of the 2nd change of direction (Figure 4c).

Figure 5b compares the flow energy at the central part of the channel. The flow energy, calculated through Bernoulli's equation, is higher for TPA approach (red dotted line) in comparison with PSM (red dashed-line) and free flow (red continuous), both almost identical. However, the effect of the PSM method is clearly seen when comparing not only the piezometric head (green dashed-line) but also the distance where the pressurized section arrives (grey dashed-line), which is between the distance obtained with PSM method (grey dotted-line) and free surface flow (grey continuous line). When the pressurized area ends, the flow in TPA tends to behave in similar way than without considering the lid. However, the faster velocity produced upstream generated less water depth downstream of the pressurized area (Fr > 1).

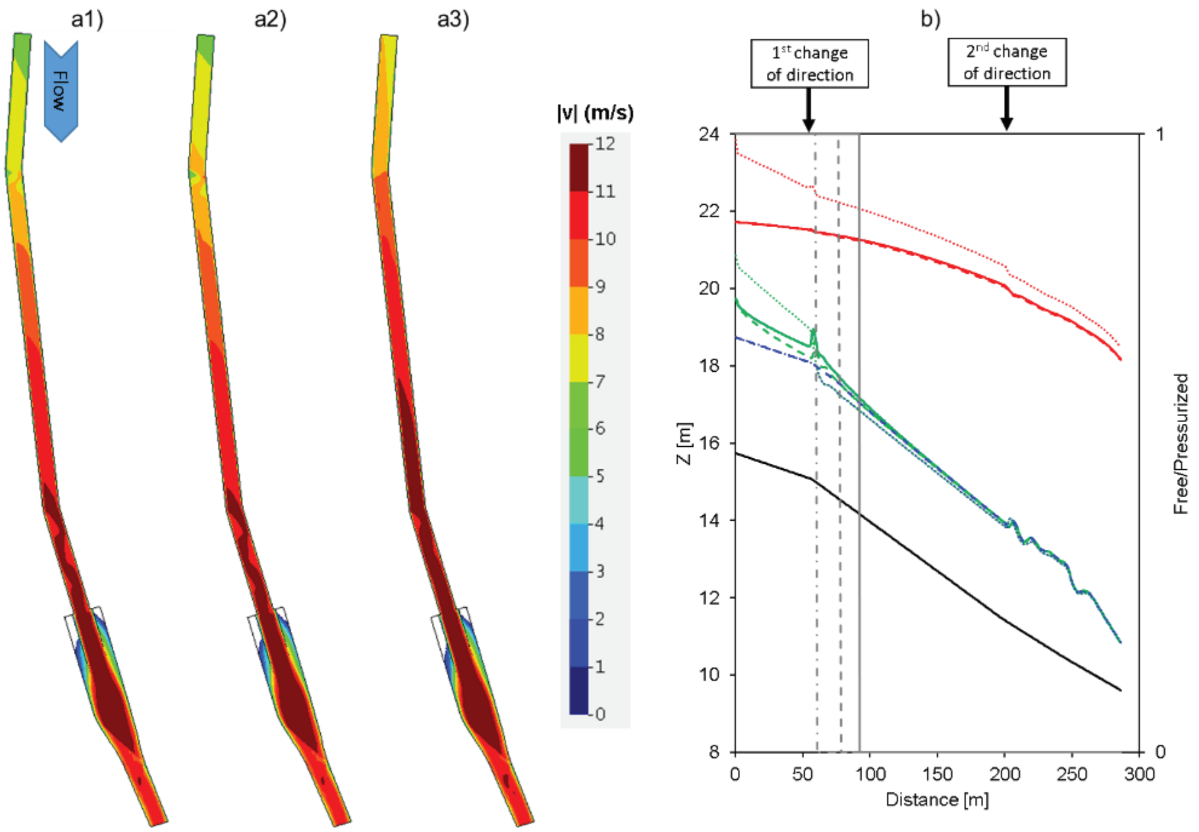


**Figure 5.** (a) Map of velocity: free surface (1), PSM (2) and TPA (2). (b) Longitudinal profile of energy: $H$ is the total flow energy evaluated through the Bernoulli equation (red line); $H_{piez}$ is the piezometric energy considered as the sum of the pressure term and the water elevation); $H_{we}$ is the water elevation energy (blue line); and the black line is the bottom of the channel. Grey lines denote the distance of the pressurized / free surface interfaces.

### 3.2. Case Study 2

Figure 6 shows the maximum water elevation reached during the simulation. When the bridge is considered as a line at the upstream boundary of the deck (Figure 6a), a pressurized area would potentially be produced and localized at the left side of each span of the bridge (black area downstream the bridge). These regions increase when the lid is considered, reaching the pressurized area almost a half of the right span for both PSM (Figure 6b) and TPA (Figure 6c) methods.

This behavior is consequence of the main direction of the flow, which approximates to the bridge with an angle of about 30º. Thus, the left side of both spans concentrated much of the flow of the flood (Figure 7), especially for PSM (Figure 7b) and TPA (Figure 7c) methods.

The general behavior of the flood is depicted in Figure 8a, where the flood attenuation when considering the bridge as a line (green continuous line) differs from both PSM (blue dashed-line) and TPA (red dotted-line) methods. Despite the pressurized method presented differences in the flow behavior at the lidded area (Figure

7b and 7c), the amount of water that trespasses the structure is almost identical (Figure 8b), being greater than the discharge evaluated through bridge equations (grey continuous line). Thus, the consideration of lids not only improved the flow behavior upstream, through and downstream of the bridge but also produced significant changes in the attenuation of the flood.

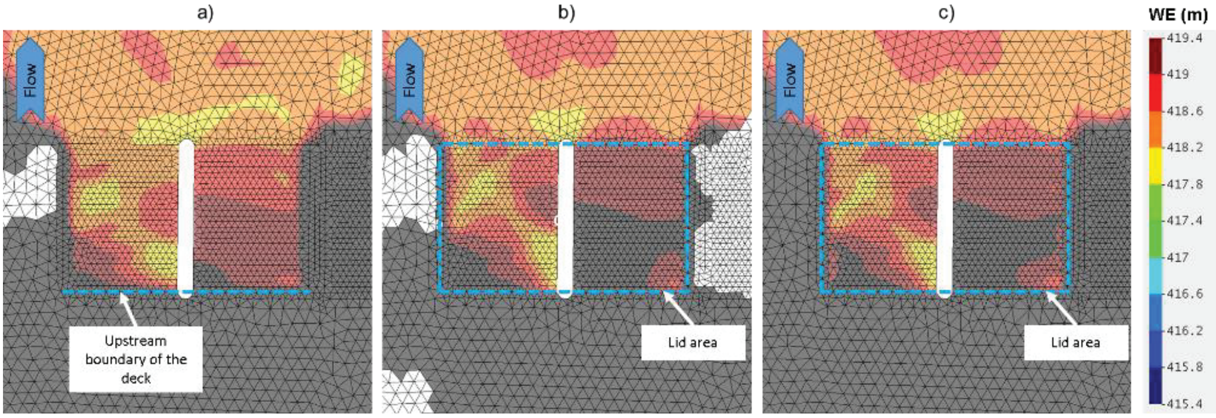


**Figure 6**. Maps of maximum depth at the bridge area considering the bridge as a line (a), as a lid through PSM (b) and TPA (c).

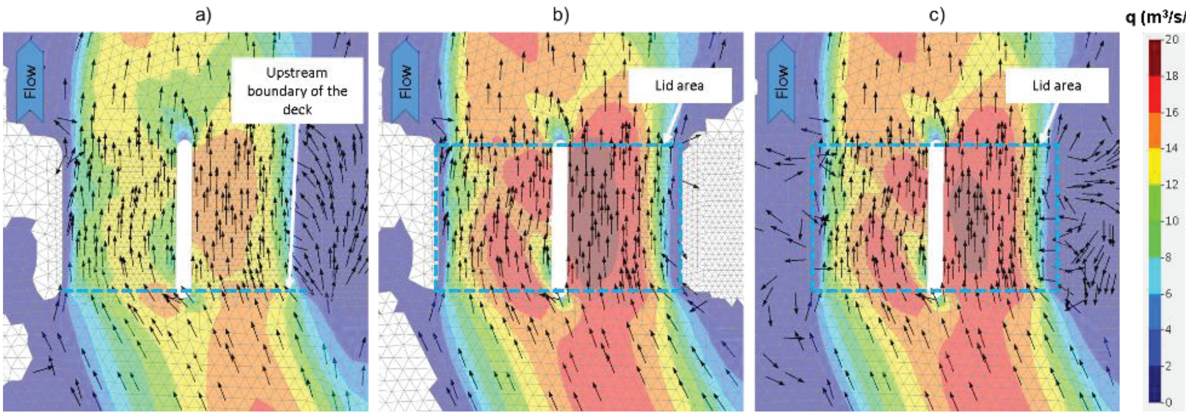


**Figure 7**. Maps of maximum specific discharge (colored) and flow direction (rows) at the bridge area considering the bridge as a line (a), as a lid through PSM (b) and TPA (c).

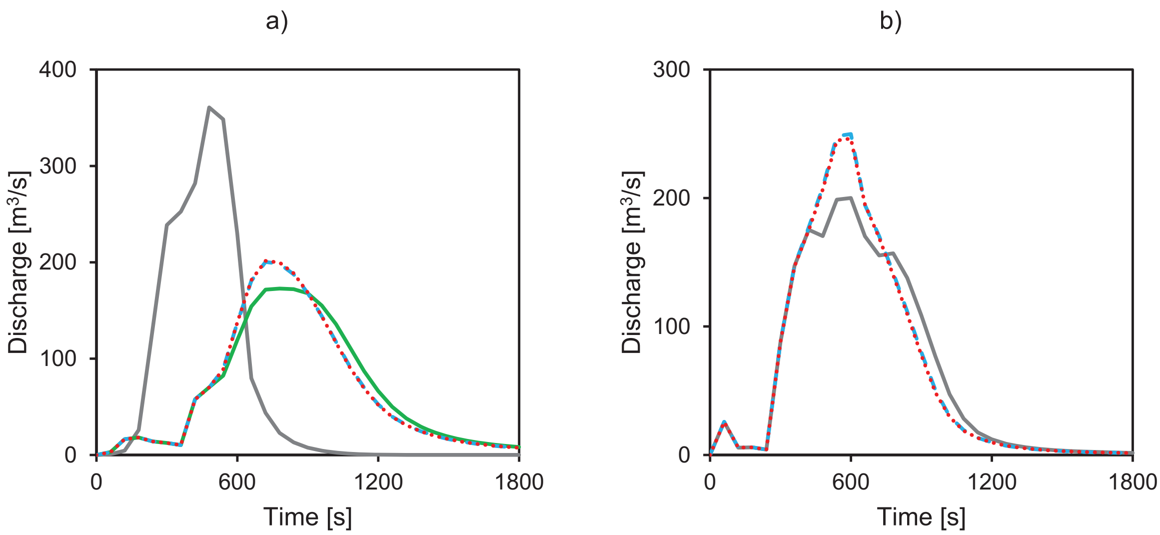


**Figure 8.** Flood attenuation (a): inlet discharge (grey continuous line); outlet discharge for the bridge as a line (green continuous line), as a lid with PSM method (blue dashed-line) and as a lid with TPA method (red

dotted-line). Discharge through the bridge considering it (b): as a line (green continuous line), as a lid with PSM method (blue dashed-line) and as a lid with TPA method (red dotted-line).

## 4. CONCLUSIONS

Numerical modeling of hydraulic structures is paramount over when carrying out flood studies. 2D-SWE-based models usually incorporates bridges as a line, the geometrical properties being implemented at the upstream boundary of the bridge deck. The flow through the bridge is usually evaluated by means of 1D empirical bridge equations, neglecting its width in the flow direction and being only valid when the flow is mostly 1D and perpendicular to the bridge deck.

Two common numerical approaches, Preissmann Slot Method (PSM) and Two-Component Pressure Approach (TPA), are extended to 2D framework to account for vertically confined flow conditions using a 2D-SWE-based model. Both numerical strategies differs, being PSM based on the consideration of indefinitely extended slot to the crown of the conduit that introduces an artificial free surface flow regeneration; while TPA is based on the consideration of the total pressure as the sum of two components, a hydrostatic pressure and a dynamic pressure.

The application of these methods to two real study cases showed that, in general, the TPA is more energetic than PSM because of the consideration of a dynamic pressure. Due to the effect of these methods in the hydrodynamics, the extension of the potential confined areas slightly differs from the areas finally pressurized when both methods are considered in the numerical model. Additionally, the consideration of confined areas to simulate bridges not only overcomes the problem of the consideration of 1D empirical equations but also fine-tunes the general flow behavior upstream, through and downstream of the bridge.

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