# NUMERICAL MODELING OF THE FLOW ON A DAMAGED WEIR APPLICATION TO THE CAVAILLON RIVER, HAITI

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## ABSTRACT

Haiti is one of the most vulnerable countries to floods and inundations. The development of infrastructures enabling systematic river monitoring is quite inexistent and consequently hydrologic and hydrographic data are really scarce. In the frame of an academic cooperation project aiming at enhancing the local capabilities to manage Haitian rivers, the Dory weir is studied because it will be used as upstream boundary condition for further flow simulations. However, due to past severe flow conditions, the weir is seriously damaged and is no more working in standard conditions. So, three different approaches are used to re-build a stage-discharge relation. Recent floods in May 2016 have recorded a set of water level and river discharge measurements. Added to previous field campaigns, these form a first estimate of stage-discharge relation. Then, detailed numerical simulations using OpenFoam are used to generate several flow scenarios on the weir, considering its exact damaged geometry, in order to rebuild a local stage-discharge. The added value of this detailed numerical approach is discussed by comparing a simple approach in defining an equivalent standard profile from which the stage-discharge relation. The objective of establishing a proposition for a stage-discharge relation from numerical approach is completed. Even if some of this approach could be further improved, the OpenFoam model can be easily adapted to other similar applications and researches including the integration of a specific shape or topographic surface. The most important benefit of the present work is therefore the establishment of a numerical-based reproducible method to generate stage discharge relations from real topographies that could, as in Dory's case, be deteriorated and differ from standard shapes.

**Keywords:** Damaged weir; stage-discharge relation; CFD simulation; Haitian River.

## 1 INTRODUCTION

Haiti is probably one of the most exposed countries to dramatic floods and inundations due, among other, to intense deforestation. Haiti is also extremely poor in hydrologic and hydrographic data, as this is not considered as a priority in a context numerous social and economic emergencies. The present work is done in the frame of a cooperation program funded by the Belgian Cooperation Administration (ARES-CCD) that aims to develop, through an exemplary watershed and river reach along the Cavaillon River (Figure 1a), a simple and repeatable methodology for enhancing hydrologic data and designing flood protection procedures.

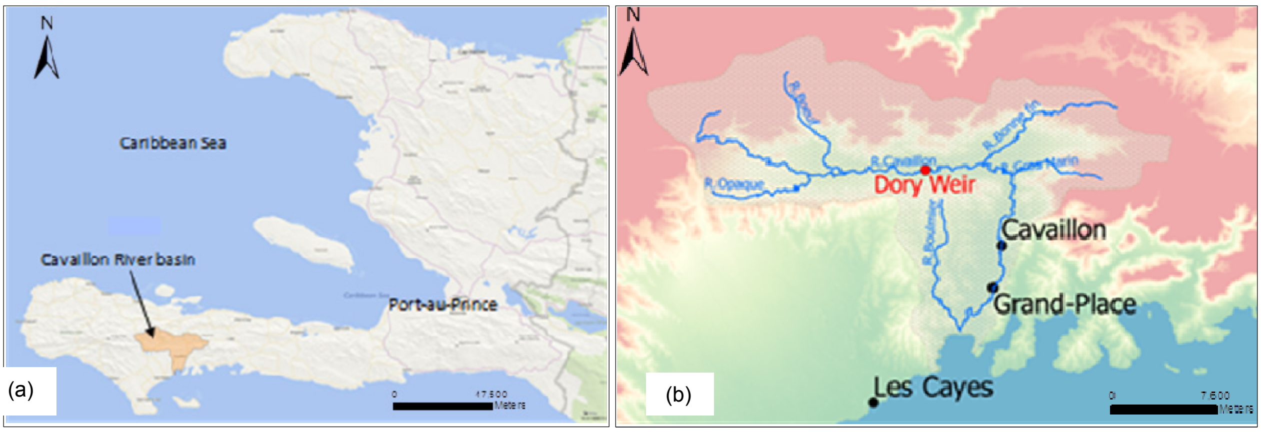


**Figure 1.** Localization of the studied river reach: (a) general map of Haiti and indication of the Cavaillon river basin, (b) Details of the Cavaillon River and tributaries.

Within this project, the discharge in the river is one of the important required data. The Dory weir, built for irrigation purpose, represents the upstream limit of the studied reach (Figure 1b). It provides a possibility to evaluate the river discharge from a continuous water level measurement at a station located 50 m upstream of the weir. Unfortunately, the infrastructure is in a very bad condition as time and recurrent floods have considerably degraded the initial weir profile (Figure 2). The weir crest is no longer horizontal (see Figures 2a and 2c), the upstream approach is partly invaded by sediments (Figures 2b and 2d) and the concrete apron downstream is partly destroyed by uplift pressures (Figure 2a and 2d).

**Figure 2.** (a) Damaged concrete slab on the downstream face of the weir (b) general view of the Dory weir (c) aerial view of the crest and the downstream slab d) damaged crest and upstream sedimentation.

The aim of the present work is to build a stage-discharge relation for the Dory weir, considering that no data are available about the design and the construction of this weir and that the damages have the consequence that it is certainly not working in standard conditions. So, in order to obtain a usable stage-discharge relation for this damaged weir, three complementary approaches are used: (1) in situ surveys, (2) numerical simulations using the free Open foam software, and (3) tentative application of the classical theory of weir flows, in order to extrapolate the stage-discharge relation beyond the limits of observations.

## 2 FIELD SURVEY

In 2015 and 2016, dense topographical surveys were conducted manually (*i.e.* using a portable total station) in Dory, leading to detailed bathymetric data of the weir and surroundings. Form this data, a three-dimensional model of the weir could be constructed (Figure 3). These measurements highlighted the main defects of the weir. First, the crest is no longer horizontal, and presents a difference of 0.23 m between the left and right bank, a difference of 0.29 m between the highest and lowest point with severe irregularities along the crest. Secondly, significant sediment deposits upstream reduced the weir crest level to only 0.32 m above the upstream bottom, while it is about 0.79 m at its maximum. Finally, as illustrated in Figures 2, the concrete apron and the downstream face of the weir were seriously damaged during past flood events, resulting in a complex downstream bathymetry along all the cross-section.

 

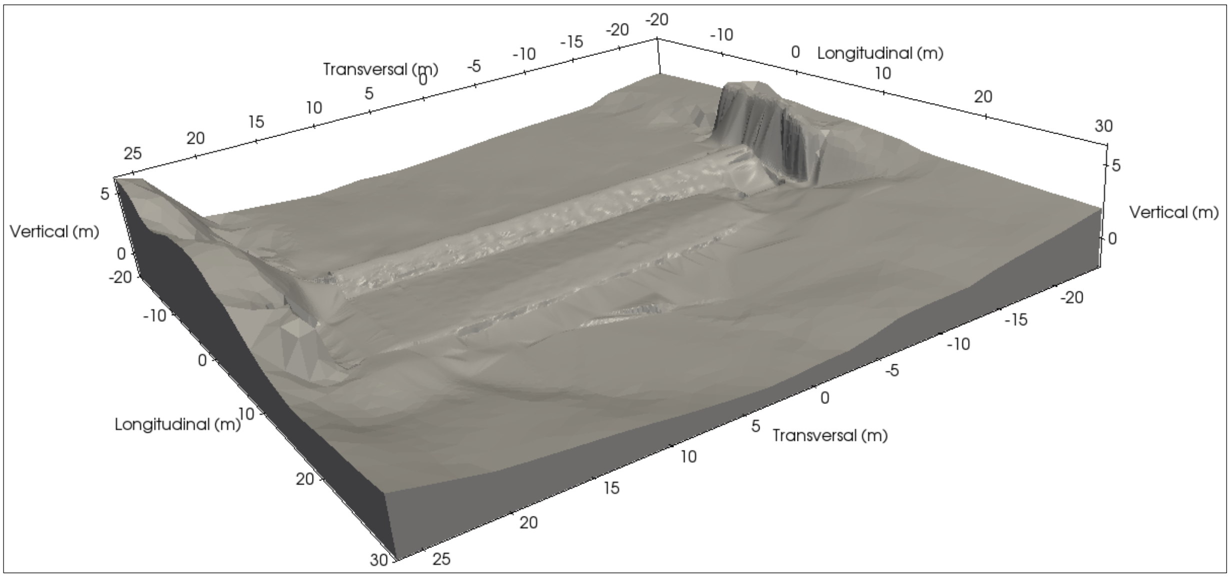


**Figure 3.** Three-dimensional model of the weir obtained from the topographical survey.

The three-dimensional model of Figure 3 is less accurate near sharp geometry changes, especially near the banks. Moreover, as shown in Figure 4b, a radial gate presents on the left bank to guarantee a minimum flow in the river even if the upstream water level does not reach the weir crest. This radial gate is not included in the topographical model. Due to these considerations, the useful section of the weir on which we can perform further calculations and simulations is limited to a 28 m width section (represented by the blue box in Figure 4a).

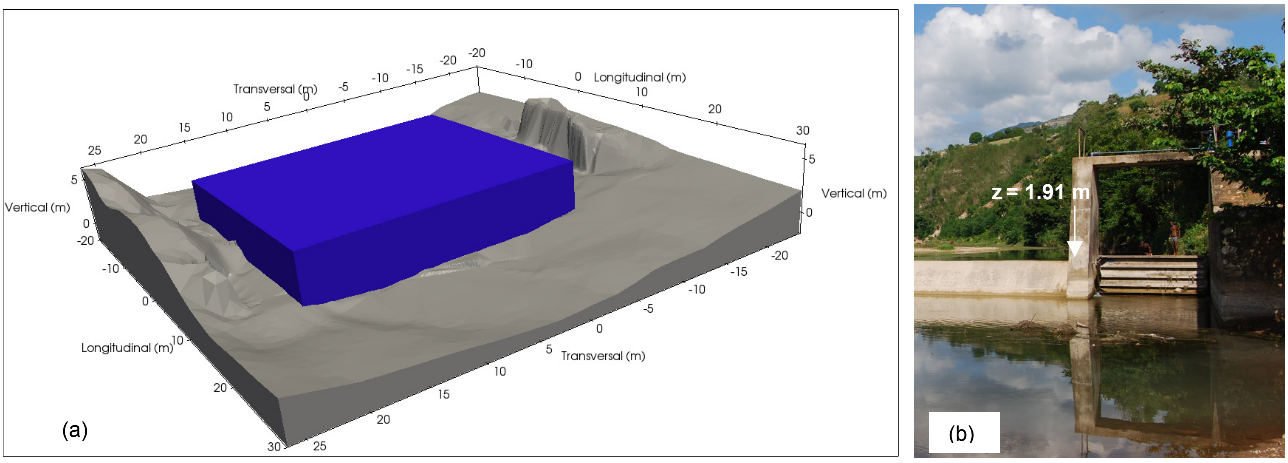


**Figure 4.** (a) Useful section of the weir on which reflection is performed (b) Picture of the right bank located gate.

The field campaign also included stage-discharge measurements. The water level was measured 50 m upstream from the weir, while velocity measurements by propellers, in a cross-section located 66 m downstream of the weir, were used for estimating the discharge by integration on the cross-section area. Unfortunately, conditions to obtain regular, good quality measurement covering a broad spectrum of values are not fulfilled. First, the whole region mainly suffered from drought during the last five years, reducing the frequency and intensity of precipitation events. Moreover, as the region is difficult to access (without paved road, tributaries to be crossed by fording), any climatic event makes transport to the Dory area even more difficult. Due to technical difficulties and lack of maintenance capabilities, the installation of automated measurement stations is impossible. In consequence, only low discharges could be observed, up to 27.94 m³/s, even if we know, after Hurricane Matthew, much larger discharges can occur in the river. The scarce available measured points, measured from a common reference point at the base of the right bank, $z$ = 1.91 m (Figure 4b), are listed in Table 1.

**Table 1.** Available water level and discharge measurements.

| Upstream water level (m) | 2.16 | 2.22 | 2.25 | 2.3 | 2.36 | 2.36 |
|---|---|---|---|---|---|---|
| Discharge ($m^3/s$) | 12.01 | 15.66 | 16.56 | 21.53 | 24.29 | 27.94 |

In conclusion, even if intuitively, the field approach seems to be the most appropriate to reconstruct a stage-discharge relation for the weir, the conditions in which any field campaign has to be conducted make it necessary to use a combined approach with theoretical reflection and numerical simulation as proposed in this work.

## 3 NUMERICAL APPROACH

### 3.1 Open foam model

The Open Foam software was used to simulate the flow over the Dory weir for several discharge conditions. This software solves the Navier-Stokes equations by a Volume of Fluid method (Hirt and Nichols, 1979), and, for the present application, the inter Foam solver was applied, which consists in a solver for two incompressible and immiscible fluids. So, the water flow and a layer of air above it are represented, the interface between these two phases being captured by a phase-fraction based interface capturing approach. In other words, in each computational cell, the fluid state is described by the value of a variable, $\alpha$ representing the relative volume of water (or air) in the cell, with $\alpha = 1$ corresponds to a cell occupied by fluid only, and $\alpha = 0$ corresponds to a cell with air only. The free-surface then located in cells with an $\alpha$ value between 0 and 1.

In order to select the best appropriate parameters of the simulation, *i.e.* mesh size, local refinement, and turbulence closure model that allow for accurate results and reasonable computational time, a convergence analysis was performed (Roelandt and Verschoore, 2016). As a result, the Dory weir and the surrounding bathymetry were discretized with finer refinement close to the weir. As regards the turbulence closure, the k- $\omega$ SST model was selected for providing the more stable results, as it combines the robustness of the k-w model near the walls and the performances of the k-$\varepsilon$ model away from the walls.

During the first study, only 2D-V simulations were run on a limited number of vertical slices in the complete 3D model of the weir, in order to limit the computational time and to obtain a first series of results that will, in a later study, be compared to full 3D simulations.

### 3.2 Applied method

The weir is divided into five representative slices (Figure 5). For each slice a stage-discharge relation is established from the numerical simulations. These five relations are then merged in order to obtain a global relation for the whole structure.

Since the effective part of the structure is located between the transversal coordinates -11 m and 17 m (Figure 4) measured along the crest axis, each slice has a width of 5.6 m. For each slice, the central cross section is chosen to represent the flow.

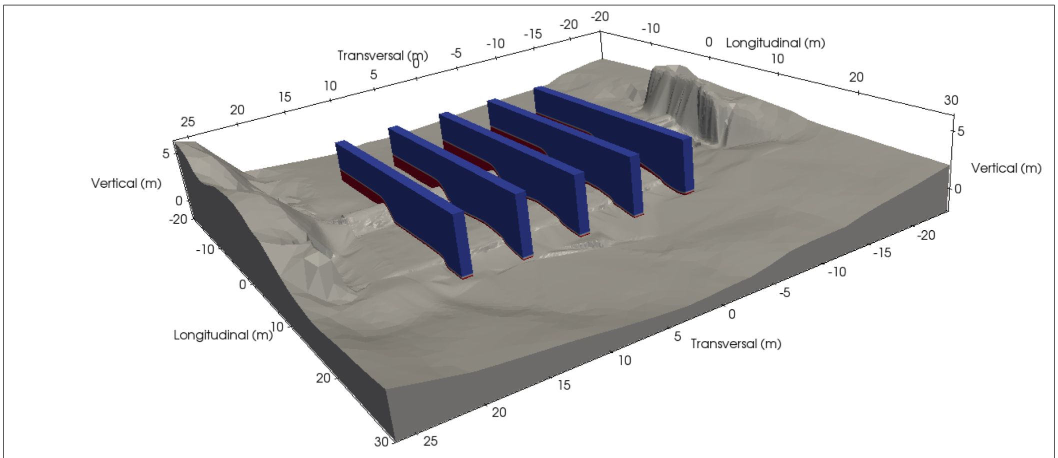


**Figure 5.** Five simulation slices representing each a 5.6 m wide portion of the weir.

In order to obtain a relation between the upstream water level and the discharge over the slice, simulations are achieved for several inlet flow conditions, since this is the variable that can be easily modified in the solver. The selected flow conditions span over the range of observed discharges (Table 1). Figure 6 shows the steady-state flow observed for four different discharges, and the corresponding upstream water level (according to a common reference explained above) that can be deduced from the simulations.

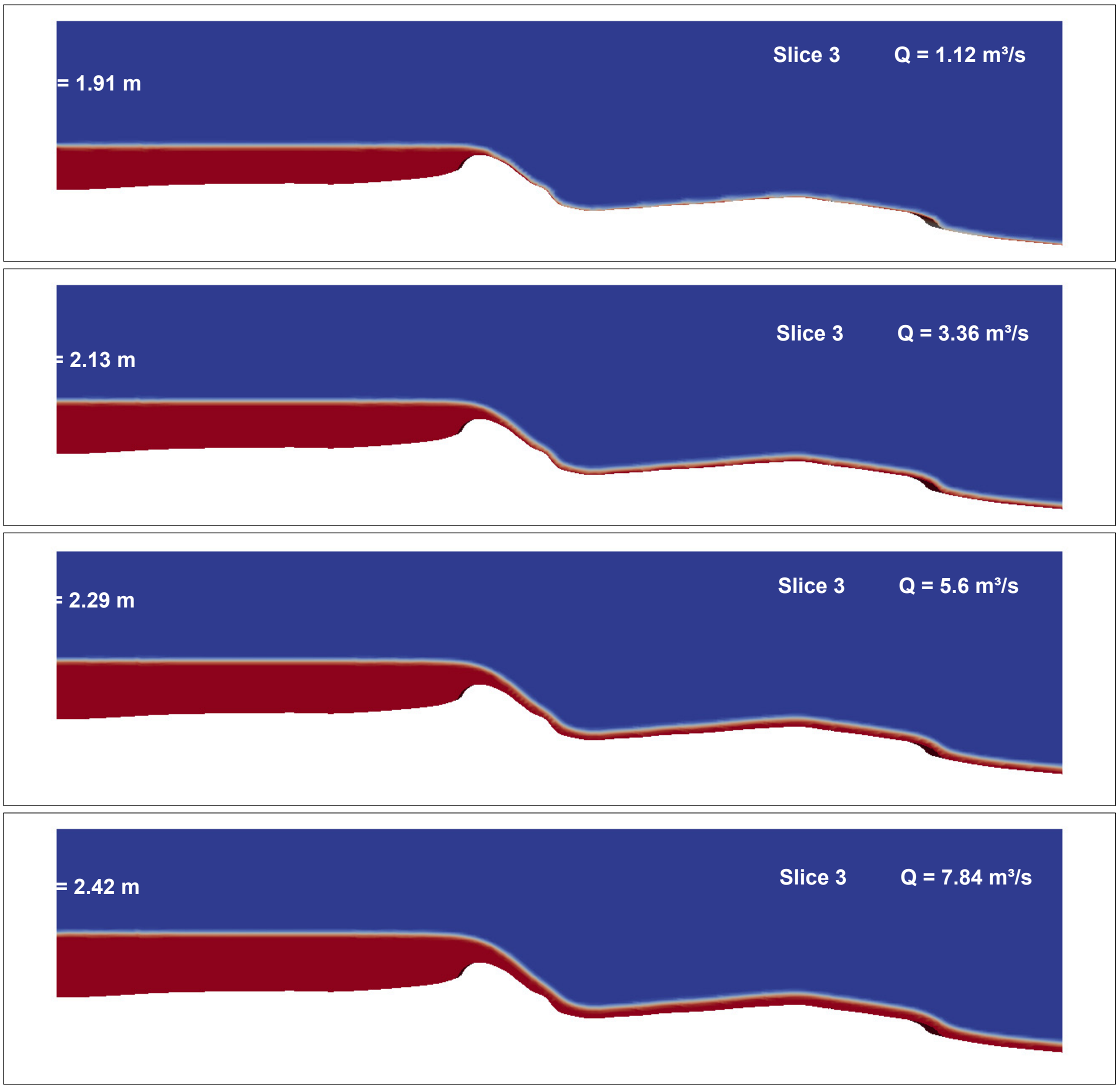


**Figure 6.** Simulation results on slice 3 with four discharges (1.12 $m^3/s$, 3.36 $m^3/s$, 5.6 $m^3/s$, 7.84 $m^3/s$) – Red is water, Blue is air, transition is clearer.

The free-surface is found as the location where the $\alpha$ variable representing the water/air ratio of an element is equal to 0.5. Using this condition, the free surface can be extracted as illustrated in Figure 7.

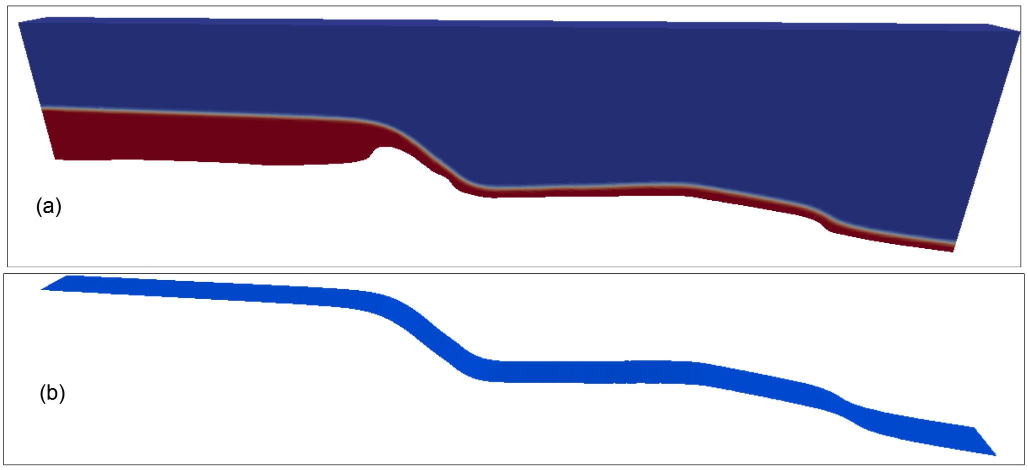


**Figure 7.** (a) Simulation of the slice 3, $Q$ = 5, 6 $m^3/s$, and (b) limit layer between water and air ($\alpha = 0.5$).

 

Couples of point ($z_{upstream}$, $Q$) were calculated for each slice in order to build a specific relation between the discharge and the upstream water level. The resulting relations are illustrated in Figures 8a-b-c-d-e. These relations are then combined to establish a single relation considered as representative for the complete weir (Figure 8f). This latter relation is expressed in terms of the upstream water level measured from the common reference system, and not in terms of the head, and the actual head cannot be defined with respect to the crest level because the crest is not horizontal.

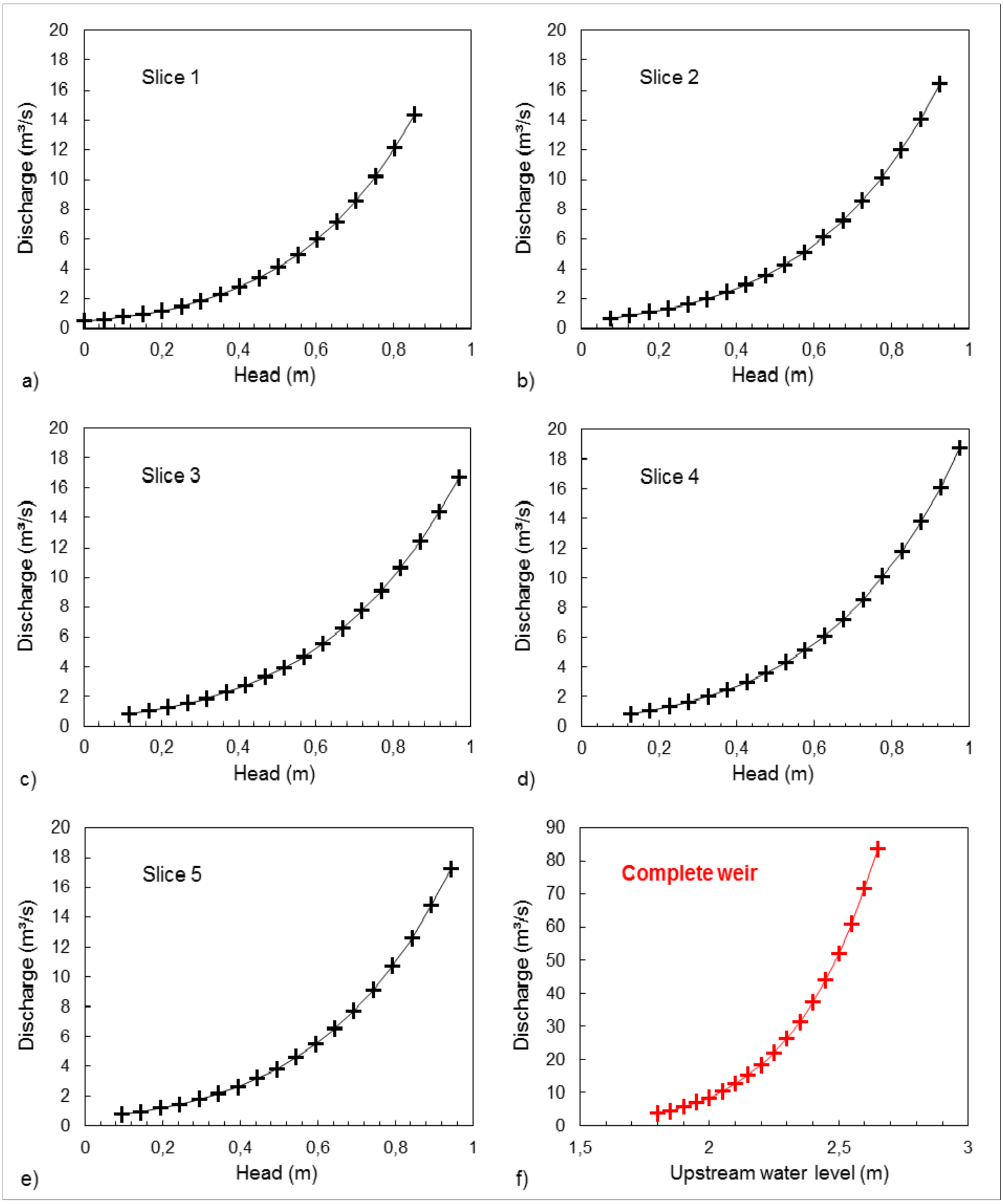


**Figure 8.** Stage discharge relations calculated for (a) slice 1, (b) slice 2, (c) slice 3, (d) slice 4, (e) slice 5, and (f) the complete weir.

 

## 4 THEORICAL APPROACH

If the use of sophisticated approaches seems to be promising, it could be instructive to observe an added value this work has in comparison with a basic idea, replacing the actual damaged Dory weir by an equivalent simple standard profile for which the stage-discharge relation could be extrapolated beyond the range of measurements. In the present work, the exercise is only done for the basic assumptions, *i.e.* limitless upstream approach depth, vertical upstream face, no influence from downstream flow and negligible inlet velocity.

To build a standard profile, a design stage ($H_0$) has to be defined. This design stage is indeed an unknown, because there is no information available about the design and construction of the weir. Two methodologies to find the design conditions are developed hereunder. The first idea was to fit the profile of a slice directly with a standard profile through the Eq. [1]. By adjustment of $H_0$, minimizing the least mean square error, it is possible to obtain a curve fitting with the theoretical standard bathymetry (Figure 9a). The normal stage found is $H_0 = 0.065$ m. Two elements are however questionable: (1) how to choose the representative slice along the crest to define a "mean" standard profile? (2) Does the geometrical similitude ensure hydraulic similitude? To answer the second question, an alternative way to build an "equivalent" standard profile was developed. Based on numerical simulation results, the stage discharge relation obtained from the OpenFoam model and Eq. [2] with $\mu_0 = 0.492$ were compared. By adjusting the stage-discharge relation to the one obtained from the OpenFoam model and minimizing the least mean square error, as shown on a log-log graph in Figure 9b, another estimation of the normal stage $H_0$ could be obtained. The value found is $H_0$ = 0.635 m.

$$\frac{y}{H_0} = 0.47 \left(\frac{x}{H_0}\right)^{1.8} \quad [1]$$

$$Q = \mu L \sqrt{2g}\, H^{1.5} = \mu_0 \left(\frac{H}{H_0}\right)^{0.17} L \sqrt{2g}\, H^{1.5} = \frac{\mu_0 L \sqrt{2g}}{H_0^{\ 0.17}}\ H^{1.67} \quad [2]$$

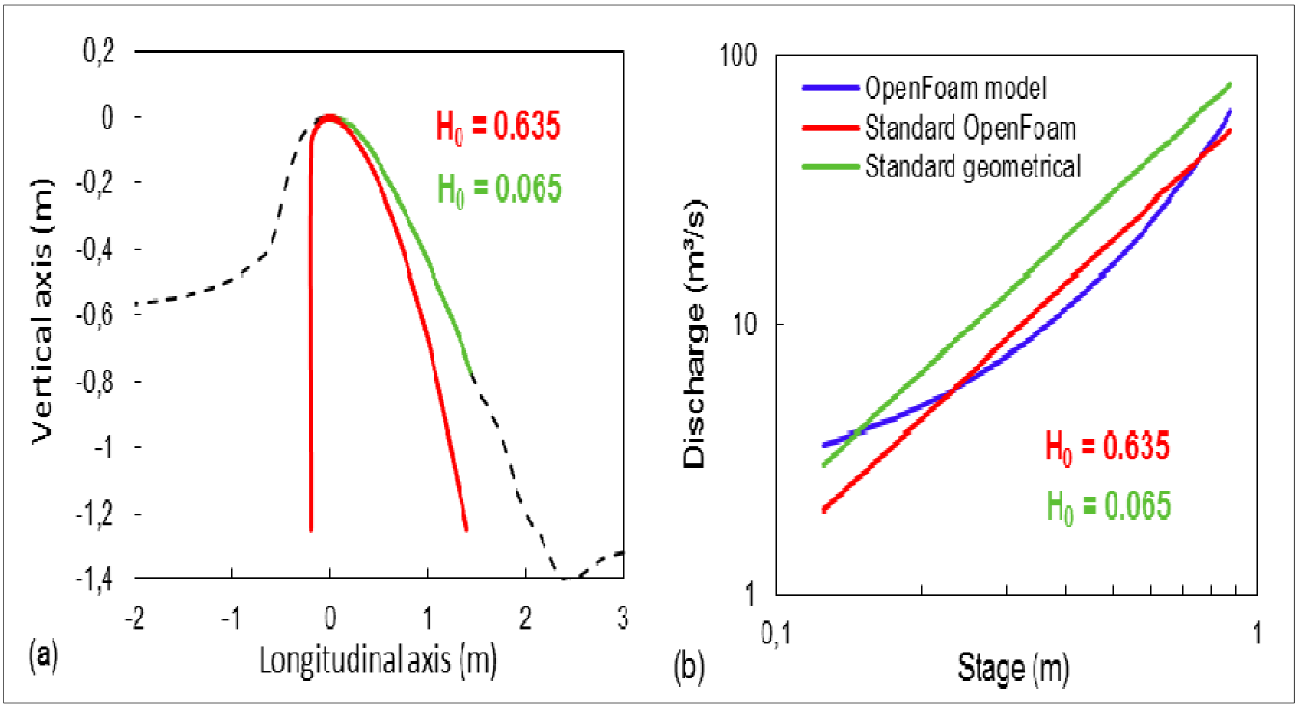


**Figure 9.** (a) Standard profiles (geometrical and OpenFoam) for their respective nominal head with background central slice profile (dotted line) (b) Comparison Stage-Discharge relations built by OpenFoam model and two equivalent standard profile fitted to geometrical shape and to OpenFoam model results.

## 5 COMPARAISON BETWEEN THE DIFFERENT APPROACHES

Figure 10 shows the stage-discharge relation for each of the approaches developed in this paper. The poor availability of field data encouraged to use alternatives methods to represent the flow over the Dory weir. First, it is interesting to notice that the best approximation of the measured field data is the one based on the OpenFoam numerical results (blue curve in Figure 10). Moreover, it can be observed that there are two ways of fitting an equivalent standard profile for the Dory weir, based on geometry or numerical results, which give significantly different results. So, it seems more appropriate to consider in terms of hydraulic convergence than pure bathymetric data fitting.

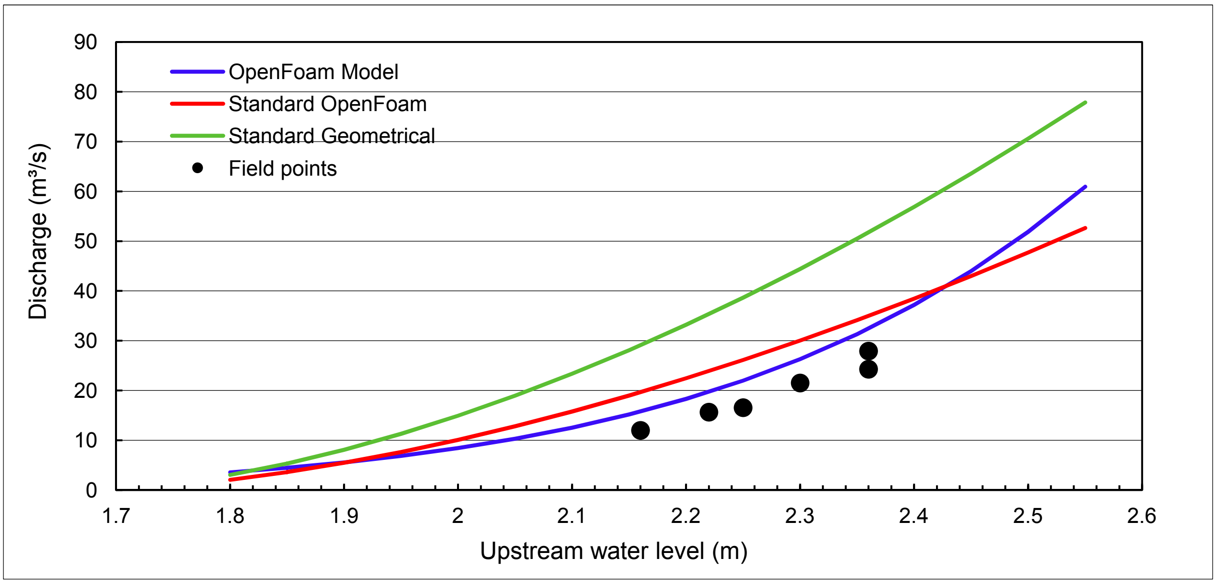


**Figure 10.** Stage-discharge curves obtained from the different methods.

## 6 CONCLUSIONS

The damaged weir of Dory on the Cavaillon River in Haïti will be used as an upstream boundary condition of a flow model developed in frame of a scientific cooperation project. Therefore, a reliable stage-discharge relation is required. Unfortunately, no information was available about the design of this weir. So, using scarce measured field data, the classical weir theory and detailed numerical simulations, a new stage-discharge relation was constructed. The results showed that the numerical simulations, even if achieved in a simplified way using only five representative slices of the weir, provided interesting results. These appear to be close to the field measurements, giving some confidence to use such models.

Nevertheless, even if this work demonstrates the merits of the combined approach, it also brings up some questions. In view of the divergence between the standard Open foam equivalent weir (red line in Figure 10) and the detailed Open foam model (blue line in Figure 10) for higher discharges, the question of the reliability of the curves arises, especially if it is to be used for extreme cases.

Further work will be carried out to obtain more information from the Open foam simulations. In particular, a new topographical survey was conducted and the data will be treated in order to improve the accuracy of the Open foam model close to the banks. Also, the radial gate located on the left bank will have to be included in the model in order to represent the overflow in cases of very high discharges. Finally, the full 3D simulations with this detailed model will be carried out to compare to the current five-slice model.

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