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Performance assessment of two-dimensional hydraulic models for generation of flood inundation maps in mountain river basins

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Abstract

Hydraulic models for the generation of flood inundation maps are not commonly applied in mountain river basins because of the difficulty in modeling the hydraulic behavior and the complex topography. This paper presents a comparative analysis of the performance of four two-dimensional hydraulic models (HEC-RAS 2D, Iber 2D, Flood Modeller 2D, and PCSWMM 2D) with respect to the generation of flood inundation maps. The study area covers a 5-km reach of the Santa Bárbara River located in the Ecuadorian Andes, at 2330 masl, in Gualaceo. The model's performance was evaluated based on the water surface elevation and flood extent, in terms of the mean absolute difference and measure of fit. The analysis revealed that, for a given case, Iber 2D has the best performance in simulating the water level and inundation for flood events with 20- and 50-year return periods, respectively, followed by Flood Modeller 2D, HEC-RAS 2D, and PCSWMM 2D in terms of their performance. Grid resolution, the way in which hydraulic structures are mimicked, the model code, and the default value of the parameters are considered the main sources of prediction uncertainty.

Keywords: Two-dimensional hydraulic models; Flood modeling; Flood extent; Water surface elevation; High mountain river; Ecuador

1. Introduction

Floods are natural processes caused by weather extremes, which inundate floodplains, and their impacts include economic losses, environmental problems, and human casualties (Cook and Merwade, 2009; Hartnett and Nash, 2017). It is expected that climate change will affect the frequency and hazard of flooding, through its impact on the intensification and acceleration of the hydrological cycle (Hirabayashi et al., 2013). Effective flood management requires flood inundation mapping, probabilistic estimates of potential damage and risks in flood zones, and the design of a master plan for flood risk mitigation. Inundation mapping has become a key measure due to the important information it provides, such as the water depth and flood extent, which are essential for efficient flood risk management (ShahiriParsa et al., 2016).

Hydrodynamic modeling of a river with floodplains requires the use of numerical methods to solve the conservation equations for free-surface flow under usual complex conditions. Since numerical models are a simplified representation of reality, a key feature of hydrodynamic modeling is an adequate representation of the topography of the river channel and adjacent floodplains (Casas et al., 2006). There are several numerical tools which allow rivers and floodplains to be modeled with one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D) approaches (Bladé et al., 2014a). Despite differences in model capacity and accuracy, to study the effects of flood propagation on rivers, and in particular to estimate flow velocities and water levels, 1D models have been used most often (Papaioannou et al., 2016). In 1D modeling it is common to consider a river as a line and channel geometry as a property of each node on the river line.

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On the other hand, in a 2D model a river is no longer discretized as a line with a series of cross-sections, but as a mesh consisting of a series of polygonal cells representing the topography of the main channel and floodplains.

In more complex river systems it is likely that a 1D model will deviate too far from reality, whereas a 2D model with horizontal dimensions predominating over vertical dimensions can lead to a more realistic description of the case. The evolution of numerical methods and the development of powerful computational tools, which facilitate the application of more complex approaches, have led to increasing use of 2D hydraulic models (Bladé et al., 2014a). Recently, several studies have compared the performance of 1D and 2D hydraulic models for river flood simulations (e.g., Horritt and Bates, 2002; Papaioannou et al., 2016; ShahiriParsa et al., 2016).

Digital elevation models (DEMs) and numerical solution schemes are essential requirements in 2D hydrodynamic modeling. The recent growth in the availability of DEMs from different sources (with spatial resolution and accuracy varying with sources) has facilitated their incorporation into hydrodynamic modeling (Horritt and Bates, 2002). There is a wide range of 2D packages developed by commercial organizations, government agencies, research groups, and universities (e.g., HEC-RAS in Brunner (2016), Iber in Bladé et al. (2014b), TUFLOW in Syme (2001), TELEMAC in Hervouet (2000), MSN_Flood in Hartnett and Nash (2017), rapid flood spreading method-explicit diffusion wave with acceleration term (RFSM-EDA) in Jamieson et al. (2012), and the Wolf software in Archambeau et al. (2002)). Merwade et al. (2008) claimed that the numerical solution schemes of models are the most important source of uncertainty. Furthermore, hydraulic models are sensitive to the description of geometry, the value of model parameters, and the representation of hydraulic structures such as bridges, culverts, and embankments.

Hunter et al. (2008) reported one of the few studies of the performance of different 2D hydraulic models in terms of their ability to simulate surface flow in a densely urbanized area. To the knowledge of the authors, no research has been conducted to assess the performance of 2D models in simulation of the hydrodynamic behavior of high mountain rivers above 2000 masl. This study aimed at testing the performance of different 2D hydraulic models in terms of prediction of the flooded area and water surface elevation of an Andean river.

2. Materials and methods

2.1. Study area

This study was carried out in the Santa Bárbara River sub-basin located in Azuay Province (within the Andes region), in southern Ecuador, at latitude 2.87°S to 2.91°S and longitude 78.76°W to 78.79°W (Fig. 1). The study area comprises a river reach approximately 5 km long that flows across Gualaceo, with an average slope of 0.25%. The western floodplain comprises an urban area, while the eastern floodplain is mainly dominated by agricultural and recreational uses. The elevation is around 2330 masl with an average temperature of 17.6°C and annual rainfall around 960 mm (INAMHI, 2015). This area was chosen because it is prone to frequent flooding.

2.2. 2D models

The hydraulic models used in this study were selected based on the accessibility of existing 2D software packages. Table 1 summarizes briefly the main characteristics of the selected models. The methods are fully described in the cited references. Essentially, each model represents a distinct trade-off between physical representation and potential computational cost, based on the developers' assumptions (Hunter et al., 2008).

2.3. Data and model implementation

In a previous study, a one-dimensional HEC-RAS model, hereafter called HEC-RAS 1D, was validated with historical

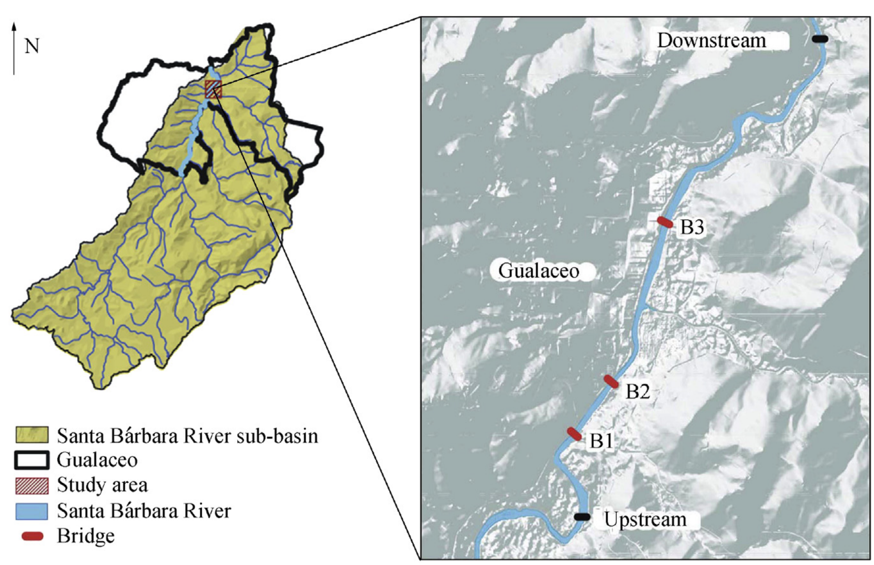

Fig. 1. Study area and high-resolution topography.

Table 1
Main features of selected hydraulic models.

Model	Developer	Solution scheme	Integrated interface	License
HEC-RAS 2D (Version 5.0.3)	US Army Corps of Engineers (USA)	A hybrid discretization scheme combining finite difference and finite volume methods (Brunner, 2016)	Yes	Public domain
Iber 2D (Version 2.4.3)	Water and Environmental Engineering Group of University of A Coruña and Flumen Institute of Polytechnic University of Catalonia and International Centre for Numerical Methods in Engineering (Spain)	Finite volume method (Bladé et al., 2014b)	Yes	Public domain
Flood Modeller 2D (Version 4.3)	CH2M (UK)	Alternating direction implicit (ADI) solver (Jacobs, 2018)	Yes	Commercial
PCSWMM 2D (Version 7.0)	Computational Hydraulics International (Canada)	Finite difference method with successive approximations under relaxation (Rossman, 2006)	Yes	Commercial

data from the flooded area along a 10-km reach of the Santa Bárbara River for flood events with a return period varying between 2 and 10 years (SENAGUA, 2014). The results of HEC-RAS 1D were used as a reference to evaluate the performance of the tested 2D models in this study.

A DEM was obtained from the National System of Rural Land Information and Technological Infrastructure Project with a high spatial resolution of 3 m × 3 m (http://www.sigtierras.gob.ec). This DEM was produced using the light detection and ranging (LiDAR) technique. Two flood events from SENAGUA (2014) with return periods of 20 and 50 years, respectively, were selected for model evaluation. Synthetic hydrographs were implemented for discharge values of each flood event. A preliminary time step analysis was carried out in order to solve stability problems. In addition, Manning roughness coefficients were selected in correspondence to the type of land coverage, in which a land cover map was used. The land cover map was developed using a geographical information system (GIS) software, and the assigned Manning roughness coefficients for different land coverage types (e.g., forest, crop, grass, and urban areas) were derived from SENAGUA (2014). Table 2 describes briefly the main conditions considered and implemented in each model.

A calibration process can be implemented for each model, with the risk that the Manning roughness coefficients change drastically for each model. The lack or non-existence of historical records of floods seriously hinders model calibration. In this study the authors decided to reconstruct the water surface elevation and flood extent for flood events using the calibrated HEC-RAS 1D.

The default mesh of HEC-RAS 2D consists of non-overlapping polygons limited to a maximum of eight sides (Brunner, 2016). Iber 2D works with structured and unstructured meshes formed by elements that can have three or four sides; this enables the combination of irregular elements with three and four sides within the same mesh (Bladé et al., 2014b). In addition, in Iber 2D, different tools have been developed for creating and editing meshes that are most suited to the needs of river flood study. For irregular or complex topography, the methodology of geometry creation in the RTIN format is implemented, adapting the approach presented in Evans et al. (2001), where the mesh consists solely of right-angled isosceles triangles. Although PCSWMM 2D can work with an unlimited number of nodes, for extensive areas it requires high computational power and more processing time, which are limitations in common use. Given this constraint, in this study a 7 m × 7 m resolution grid was used. For roughness implementation in PCSWMM 2D we followed the method described in Beck (2016) for a single mesh.

In Iber 2D, bridges were added by editing the mesh manually, while in HEC-RAS 2D, PCSWMM 2D, and Flood Modeller 2D, this option was not available. Nevertheless, culverts can be implemented as an approximation, mimicking the openings of simple bridge structures. Thus, in HEC-RAS 2D, culverts were implemented for the simulation of the openings under bridges. While bridge approximations could also be included in PCSWMM 2D and Flood Modeller 2D, they were not added because the procedure was more complex than it was for the other tested packages.

2.4. Statistical analysis

For the evaluation of the model's performance, simulation results of the selected models were compared to those of the

Table 2
Parameters considered for setting up 2D hydraulic models.

Model	Mesh type	Mesh node	Grid resolution	Bridge implementation	Manning roughness coefficient
HEC-RAS 2D	Default (polygons)	Unlimited	3 m × 3 m	Not available	Land cover map
Iber 2D	Right-triangulated irregular network (RTIN)	Unlimited	3 m × 3 m	Available	Land cover map
Flood Modeller 2D	Default (squares)	Limited	7 m × 7 m	Not available	Land cover map
PCSWMM 2D	Default (hexagons)	Unlimited	7 m × 7 m	Not available	Land cover map

previously validated HEC-RAS 1D (SENAGUA, 2014), referred to here as the reference. Thus, water surface elevation estimation from each tested model along the river reach was compared to that from the reference model, and the mean absolute difference (E) was expressed as

$$E = \frac{1}{N}\sum_{i=1}^{N}\left|L_{\mathrm{r}i} - L_{\mathrm{m}i}\right| \tag{1}$$

where $L_{\mathrm{r}i}$ is the water surface elevation simulated by the reference model, $L_{\mathrm{m}i}$ is the water surface elevation estimated by the 2D models, and N is the total number of points where simulation results were compared.

To evaluate the sensitivity of the model structure in terms of flood extent, we used the measure of fit (F) proposed by Bates and De Roo (2000):

$$F = \frac{M_1 \cap M_2}{M_1 \cup M_2} \times 100\% \tag{2}$$

where M_1 and M_2 are the simulated and observed flood extents, respectively, whereby the simulated result of the flooded area with the reference model was used as the observed value; and $\cup$ and $\cap$ are the union and intersection in GIS operations, respectively. An F value equal to 100% indicates that the two areas are exactly the same, quantitatively and spatially.

3. Results and discussion

3.1. Water surface elevation

Fig. 2 depicts the water surface elevations simulated by the reference model versus the results obtained with the four 2D hydraulic models (HEC-RAS 2D, Iber 2D, Flood Modeller 2D, and PCSWMM 2D). The water profiles were obtained by simulating the flood events with return periods of 20 and 50 years, respectively. In Fig. 2 the impacts of the three implemented culverts on the simulation result of HEC-RAS 2D are visible. This effect increases for the higher return period (with higher flow discharge). Therefore, HEC-RAS 2D is highly sensitive to the inclusion of culverts as an approximation of bridges, with a difference of up to 1 m at B1 as compared to the results of the reference model. Iber 2D presents the best performance in the water surface elevation estimation, as shown in Fig. 2. Flood Modeller 2D shows a relatively poor performance (underestimation) in the upstream reach for both flood events, but from 820 m (location of B1), the model estimates the water surface elevation adequately. PCSWMM 2D shows the poorest performance for both return periods with significant and systematic underestimation for the entire river reach.

The goodness of fit between the 2D models and the reference model shown in Fig. 2 is quantified in terms of the mean absolute difference. Table 3 depicts the E values in terms of the simulated water surface elevation. The results show that Iber 2D has the lowest E values for both return periods, followed by Flood Modeller 2D. Higher disagreement was found for HEC-RAS 2D and PCSWMM 2D, with the latter yielding the largest E values. For the best model, the mean absolute differences of water surface elevation were 0.32 m and 0.36 m, while for the poorest model, the mean absolute differences were 1.32 m and 1.61 m for the flood events with 20- and 50-year return periods, respectively.

The considerable differences between the water surface elevations obtained by PCSWMM 2D and HEC-RAS 1D may be partly due to the lower grid resolution (7 m × 7 m). This is corroborated by Li and Wong (2010) who found decreases in the water surface elevation and flood extent when coarsening the terrain dataset resolution. On the other hand, Wang and Zheng (2005) and Cook and Merwade (2009) found that

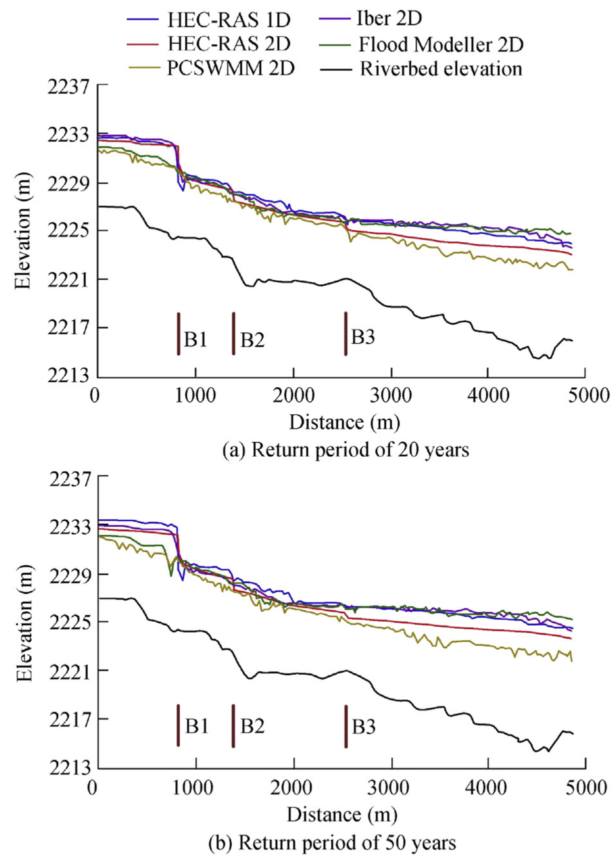

Fig. 2. Water surface elevations along study reach obtained with 2D hydraulic models compared to those simulated with reference model for flood events with 20- and 50-year return periods, respectively.

Table 3
E values in terms of water surface elevation estimations between reference model and 2D tested models for flood events with 20- and 50-year return periods, respectively.

Model	E_{RP20} (m)	E_{RP50} (m)
HEC-RAS 2D	0.65	0.78
Iber 2D	0.32	0.36
Flood Modeller 2D	0.49	0.62
PCSWMM 2D	1.32	1.61

Note: The subscripts RP20 and RP50 mean the return periods of 20 and 50 years, respectively.

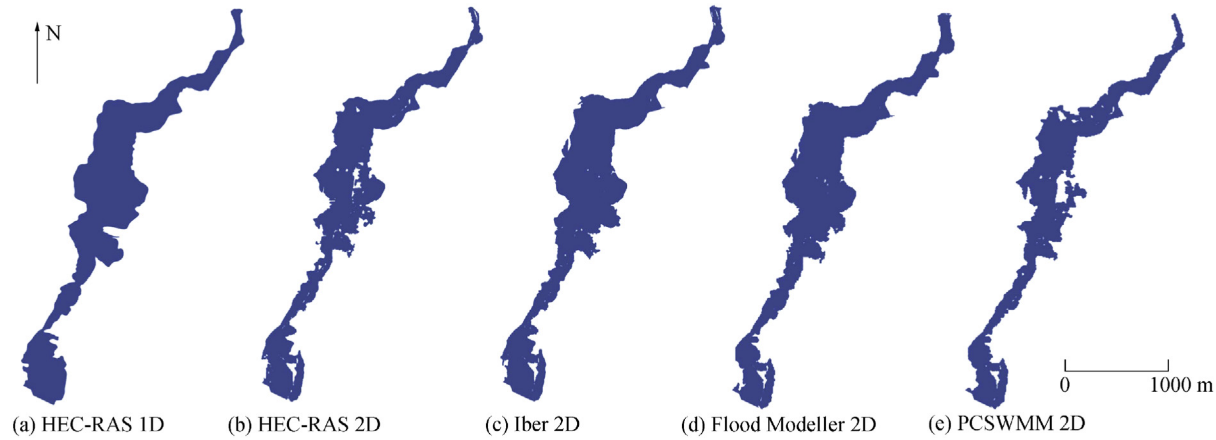

Fig. 3. Flood inundation maps for flood event with 50-year return period.

coarsening the resolution of the topographic dataset increased the flood extent as well as the water depth. In contrast, Flood Modeller 2D produced better results in comparison to PCSWMM 2D using the same grid resolution of 7 m × 7 m. This result suggests that the difference between numerical methods is a plausible explanation of the noticed disparities, as both models use the same grid resolution.

3.2. Flood extent

This section discusses the sensitivity of flood mapping results as a function of the applied solution scheme using default model parameters. Fig. 3 shows the simulated flood inundation maps of the flood event with a return period of 50 years, and the reference flood inundation map used for evaluation is presented in Fig. 3(a). For a more detailed analysis of the flood extent, we divided the river reach into seven critical zones (Fig. 4). This zonification was based mainly on the topographic conditions. Table 4 shows the inundation area of different zones obtained by HEC-RAS 1D for flood events with 20- and 50-year return periods, respectively. Zones 6 and 7 are the most important due to their extension. The floodplain delineation and the areas of different zones estimated by the four 2D hydraulic models are substantially different, as can be observed in Fig. 3(b) through Fig. 3(e).

Table 5 shows a comparison of simulated flood extents between the reference model and the four 2D models for the seven zones of the river reach. The measure of fit and estimate of flood extent for each critical zone vary with the model used, return period, and critical zone. For example, for the flood event with a 20-year return period in Zone 1, the best model in terms of performance is Iber 2D, followed by HEC-RAS 2D, PCSWMM 2D, and Flood Modeller 2D. For the flood event with a 50-year return period, Iber 2D has the best performance, followed by HEC-RAS 2D, Flood Modeller 2D, and PCSWMM 2D. In contrast, for Zone 6, Iber 2D yields the best fit for both events, followed by HEC-RAS 2D for the flood event with a 20-year return period and Flood Modeller 2D for the flood event with a 50-year return period, respectively. In this zone PCSWMM 2D shows the least agreement for both events. Finally, the results indicate that all the tested models show the poorest performance in Zone 5. This result may be explained by the influence of a tributary river at this point (e.g., backwater effect). The San Francisco River was considered in the HEC-RAS 1D modeling but not considered in the tested 2D models. Despite the use of a fine DEM resolution (3 m × 3 m), the resolution was not enough to mimic in detail the San Francisco River channel, which has a width varying between 1 and 3 m. However, in all cases the discharge of the San Francisco River was added to the Santa Bárbara River to simulate the full flow in the main zones (zones 6 and 7) downstream of the confluence. The discharge of the San Francisco River varied at around 6% of the total discharge.

Globally, Iber 2D performs best in terms of prediction of the extent of flooded area with the maximum F values of

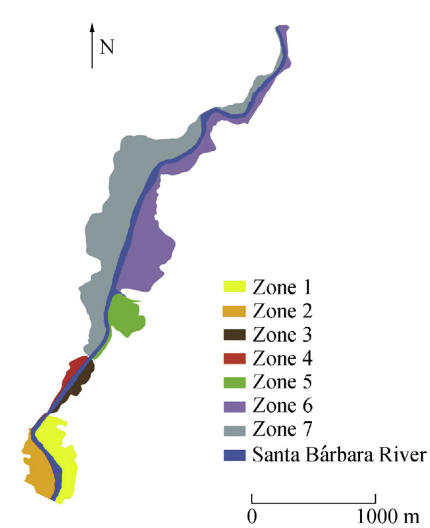

Fig. 4. Delineation of seven critical zones along river reach based on flood inundation map obtained with HEC-RAS 1D for flood event with 50-year return period.

Table 4
Inundation areas of different zones simulated with HEC-RAS 1D.

Zone	Inundation area for different flood events (hm^2)	
	20-year return period	50-year return period
1	9.32	10.48
2	6.21	7.49
3	2.46	2.89
4	1.49	1.99
5	6.44	7.75
6	29.04	30.48
7	43.66	50.91

92.6% and 94.1% for the flood events with 20- and 50-year return periods, respectively. PCSWMM 2D shows the smallest flooded area, with the maximum *F* values of 71.7% and 76.4% for the flood events with 20- and 50-year return periods, respectively. Flood Modeller 2D presents complex behavior with varying performance and without a clear trend, the maximum *F* values were 89.9% and 91.2% for the flood events with 20- and 50-year return periods, respectively. In addition, HEC-RAS 2D presents an acceptable efficiency with the maximum *F* values of 88.2% and 86.7% for the flood events with 20- and 50-year return periods, respectively.

Even though we tried to represent equal conditions in model parameterization (e.g., the Manning roughness coefficients, boundary conditions, etc.), the differences in the model code (e.g., the numerical scheme) and default calibration parameters are sources of uncertainty. This interpretation is in agreement with the research of Merwade et al. (2008). Despite the fact that the Manning roughness coefficients in the channel and floodplains have a significant impact on the estimation of water levels, this aspect was excluded in the performance assessment of the models because all of them used the same land cover map as an input.

While in the literature a debate still exists about whether a 1D or a 2D model provides a better representation of a flood event (Horritt and Bates, 2002; Tayefi et al., 2007; Papaioannou et al., 2016), it should be noted that even for the most sophisticated models, the performance of models is influenced by the quality of source of information that is available for their parameterization, calibration, and validation. This is especially critical in undeveloped countries where financial and data sources are scarce.

Table 5
Results of tested models in terms of inundation area and their comparison with results of HEC-RAS 1D.

Zone	Model	Results for flood event of 20-year return period			Results for flood event of 50-year return period		
		Inundation area (hm^2)	Area difference (%)	*F* (%)	Inundation area (hm^2)	Area difference (%)	*F* (%)
1	HEC-RAS 2D	8.67	−7.0	80.2	9.10	−13.2	81.6
	Iber 2D	8.98	−3.6	80.9	9.43	−10.0	83.3
	Flood Modeller 2D	7.46	−20.0	71.4	8.56	−18.3	77.0
	PCSWMM 2D	7.82	−16.1	71.7	8.51	−18.8	76.4
2	HEC-RAS 2D	5.63	−9.3	88.2	6.60	−11.9	86.7
	Iber 2D	6.58	6.0	92.6	7.31	−2.4	94.1
	Flood Modeller 2D	4.27	−31.2	66.3	5.17	−31.0	66.5
	PCSWMM 2D	4.40	−29.1	67.7	4.90	−34.6	62.6
3	HEC-RAS 2D	2.33	−5.3	65.7	2.92	1.0	71.7
	Iber 2D	2.42	−1.6	68.7	2.99	3.5	74.0
	Flood Modeller 2D	2.50	1.6	89.9	2.97	2.8	91.2
	PCSWMM 2D	1.27	−48.4	48.3	2.36	−18.3	75.3
4	HEC-RAS 2D	1.32	−11.4	78.6	1.63	−18.1	72.8
	Iber 2D	1.37	−8.1	83.3	1.79	−10.1	80.6
	Flood Modeller 2D	1.54	3.4	80.8	1.92	−3.5	79.8
	PCSWMM 2D	1.30	−12.8	68.5	1.52	−23.6	65.1
5	HEC-RAS 2D	3.00	−53.4	40.7	4.21	−45.7	54.1
	Iber 2D	4.29	−33.4	57.7	5.37	−30.7	68.3
	Flood Modeller 2D	2.92	−54.7	35.9	4.83	−37.7	60.0
	PCSWMM 2D	2.13	−66.9	24.5	4.29	−44.6	54.3
6	HEC-RAS 2D	23.66	−18.5	74.0	27.85	−8.6	82.0
	Iber 2D	29.85	2.8	83.1	33.51	9.9	86.5
	Flood Modeller 2D	27.26	−6.1	70.4	34.00	11.5	85.6
	PCSWMM 2D	15.19	−47.7	47.2	22.74	−25.4	69.1
7	HEC-RAS 2D	35.34	−19.1	71.9	41.18	−19.1	80.1
	Iber 2D	45.01	3.1	81.5	51.30	0.8	89.0
	Flood Modeller 2D	45.36	3.9	75.1	50.73	−0.4	85.1
	PCSWMM 2D	29.62	−32.2	64.6	37.56	−26.2	72.7

4. Conclusions

In this study we compared the performance of four 2D hydraulic models (HEC-RAS 2D, Iber 2D, Flood Modeller 2D, and PCSWMM 2D) for the estimation of the water surface elevation and flood extent in a mountain river basin located in southern Ecuador. The 2D model results were compared with those of a validated 1D reference model. The comparison provided valuable insights into the framework of flood modeling and the implementation of appropriate 2D hydraulic models in high mountain rivers.

In terms of water surface elevation estimation, Iber 2D shows the best performance with mean absolute differences of 0.32 m and 0.36 m for the flood events with 20- and 50-year return periods, respectively, while PCSWMM 2D presents the largest mean absolute differences (approximately four times higher than those of Iber 2D). The same pattern is observed for the flood extent delineation. For the flood event with a 50-year return period, Iber 2D has the best fit, with the highest average F value (82%, considering the seven critical zones), while PCSWMM 2D has the lowest average F value (68%). In contrast, Flood Modeller 2D and HEC-RAS 2D present similar and acceptable performance, with the average F values of 78% and 76%, respectively. Similar results are obtained for the flood event with a 20-year return period.

According to the findings of this study the following conclusions can be drawn:

(1) The tested 2D hydraulic models can predict the flood extent and water surface elevation of mountain rivers with different levels of accuracy, under the same parameterization conditions. The model code, the default parameters, and the solution scheme are the likely causes of the observed differences.

(2) Iber 2D presents the best 2D hydraulic model for the studied conditions, followed by Flood Modeller 2D, HEC-RAS 2D, and PCSWMM 2D.

(3) Results should be treated with caution, since the application of the tested models to other reaches and flood events may reveal different behaviors.

(4) The poorer performance of PCSWMM 2D is not necessarily due to the inaccuracy of the model. A possible explanation for this might be the lower grid resolution used and by the fact that bridges were not implemented in this model.

(5) The main restriction of the 2D models remains the high computation requirements, resulting in a considerable amount of time required for calculation.

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