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Prediction of flood discharge and flood flow depth using a hydraulic model and flood marks on the trees in ungauged forested watersheds

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Abstract: It is difficult to estimate flood discharges and the flood zones as well as to design hydraulic structures in rivers without using hydrometric stations. Furthermore, using different models to determine the mentioned cases will be accompanied by errors. Therefore, flood marks on the trunks of trees located in the Babolrood riverbed were used to determine the peak discharge, flood flow depth, and flood zone in northern Iran. First, a hydraulic model for the study river was provided using topographic maps with a scale of 1: 1 000, HEC-GeoRAS extension (GIS), and HEC-RAS model. Then, the flood marks of past floods in the form of silt and clay sediments (deposits on the trees in the riverbed) were evaluated and the maximum flood flow depth was determined. Finally, the peak discharge of the past flood was estimated by the trial-and-error method to achieve the flood flow depth in the different river reaches. Then, the hydraulic model using the flow depth data was calibrated in the reaches, and, in the final step, based on the flood marks of other reaches, the model was validated. According to the results, the maximum instantaneous discharge rate of the study flood was 155 $m^3 \cdot s^{-1}$ and the maximum flood flow depth was about 2 m. Furthermore, the results showed that the flood mark data in forest lands can be used as a tool for the calibration and validation of hydraulic models. The present methodology is an efficient method for determining the flood peak discharge, spatial variation of the flood depth, and flood zone in forest watersheds without hydrometric stations.

Keywords: Babolrood River; forest lands; flow depth; flood zone; HEC-RAS model

Determining the maximum discharges is very important in river engineering studies, flood studies and natural resource management planning. Unfortunately, many rivers do not have hydrometric stations to measure the discharge and water quality. Therefore, determining the discharge of rivers in studies such as determining the riverbed boundary, flood zone, as well as designing aquatic structures require estimating the design discharge based on experimental methods or modelling (Burns et al. 2005; Asfaha et al. 2015; Waghwala, Agnihotri 2019; Kayan et al. 2021). On the other hand, hydrological and hydraulic modelling methods require a set of observational data to calibrate and validate the models (Yazdi, Salehi Neyshabouri 2015).

Along rivers without hydrometric stations, we face restrictions on access to evidence or observational data. One of nature's signs or symptoms is the flood mark. The flood mark is the effect of the highest water level on the riverbank or in floodplain. The use of flood marks is one of the observational markers that can be used in river engineering

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studies to determine the flow depth of a flood or the flood zone (Luu et al. 2018). Iranian forest watersheds, especially upstream rivers, generally lack hydrometric statistics and are generally more difficult to access than rivers in the plains (Sheikh 2014; Khaleghi, Varvani 2018). The presence of forest soils with a suitable depth leads to high erosion and, consequently, causing high turbidity and sediment loss during a flood and, as a result, flood mud is deposited on the trunks of trees as a cover of clay and silt sediments (Dalir et al. 2014; Varvani et al. 2019; Sahour et al. 2021b). The effect of clay and silt is a mark of the previous flood, the height or depth of which indicates the maximum flood depth. Therefore, flood marks on tree trunks located in riverbeds and floodplains can be used as observational data to determine the flood depth and flood zone in forest lands, and it can also be used to calibrate or validate hydraulic models, and to determine the flow depth or flood zone.

In the discussing the determination of the flood discharge in an ungauged watershed (without hydrometric data), several modelling methods, such as statistical methods, experimental methods, rainfall-runoff models, a regional flood analysis, and artificial intelligence methods, have been used (Bhadra et al. 2008; El-Hames 2012; Arsenault, Brissette 2014; Asfaha et al. 2015; Kayan et al. 2021). However, in the end, these cases provide preliminary modelling and estimation models that require further calibration and validation. The predictions of all these methods have a significant amount of associated errors and must be calibrated and validated based on observational data (Bárdossy 2007). Therefore, the use of flood marks can be considered suitable observational data for the model calibration or validation in rivers that do not have a hydrometric station and any measured discharge data (Luu et al. 2018).

The use of the HEC-RAS hydraulic model is one of the common methods used to simulate the hydraulic behaviour of a river (Hyalmarson 1988; Hooijer et al. 2004; Santos et al. 2011; Binh et al. 2019). This model simulates the hydraulic behaviour of rivers in the design discharge (intended discharge). In this model, the topographic conditions of the riverbed and floodplain, the design discharges, the type of bed cover and vegetation, and the flow regime of the river are considered. This is a high-performance model which can calibrate and validate the hydraulic behaviour of a river. It can also be used to study different scenarios by changing the model inputs. Hill (2001) evaluated the advantages of using a combination of the HEC-GeoRAS (GIS) extension and the HEC-RAS model for evaluating flood hazards. He found that this methodology can simulate the flood zone with high performance and in a short time. Moreover, the results can be presented in the form of geo-referenced data. Carson (2006) predicted the river hydraulic behaviour and evaluated the flood and bank erosion hazard in the US (Utah), where he used the recorded hydrographs to validate the model. Pistocchi and Mazzoli (2002) used the HEC-RAS model to predict the flood flow, where they calibrated the model based on the rating curve of recent floods. Balasch et al. (2011) performed flood routing using the HEC-RAS hydraulic model, where they found that the peak discharges are variable along the length of a river. Meresa (2019) predicted the streamflow in an ungauged watershed using remote sensing (RS) and an artificial neural network (ANN). According to their results, the coupling of RS and ANN can predict the streamflow with acceptable performance. Gholami et al. (2021) evaluated the streamflow using tree-rings and vessel features in forest lands in northern Iran. Their results showed that tree-rings and vessel diameter chronologies are good indicators for studying the streamflow. Sahour et al. (2021a) used tree-ring chronology and machine learning techniques for to model the streamflow. Their results showed that tree-rings can be used to estimate the stream discharge during the growth season for low flows and the mean discharges.

Unfortunately, most rivers of the forest watersheds in northern Iran do not have hydrometric stations. However, flood marks are visible on the tree trunks in the riverbed and the flood plains. Therefore, it is possible to predict the flow hydrograph by using flood marks on tree trunks and identifying the flood generating rainfall in climatology stations, thus, presenting a rainfall-runoff model (Gholami et al. 2015, 2019). Moreover, by providing hydraulic models and previous flood marks, it is possible to determine the exact peak discharge rate and calibrate and validate the hydraulic models. The goal of this study is to provide a methodology to determine the flood zone and the flood discharge based on flood marks on tree trunks in forest watersheds. Furthermore, this study provides observational data and a method to calibrate and validate the hydraulic model in order to model

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the hydraulic behaviour of floods in forest lands lacking hydrometric data.

MATERIAL AND METHODS

The study watershed is part of the Hyrcanian forests of northern Iran, which is located at range of 52°40'E to 52°55'E and 36°00' to 38°16'N (Figure 1). The study was carried out upstream of the Babolrood River, which has a watershed with forest land use and lacks a hydrometric station and river discharge data. The study watershed has an area of 350 km^2. The region has a temperate humid climate based on Amberge method (Gholami et al. 2008). A reach of about four kilometres of the Babolrood River was evaluated, in which there are a significant number of trees, such as *Fagus orientalis* and *Carpinus betulus*, in the riverbed. After the occurrence of floods in previous years, flood marks are observed on tree trunks located in the riverbed as clay and silt sediments are deposited on tree trunks. In the study to determine the past flood discharge, the flood flow depth, and finally the flood zone, studies have been undertaken using the following steps.

Determining the flood depth and flood zone. Flood marks on the tree trunks were identified using field observations and the maximum depth of the previous flood flow (the year 2019) was measured using a measuring stick and GPS set (Figure 2A–B). The maximum height of the sediment on the tree trunks can be used to determine the depth of the flood flow or the flood zone. The highest level of the flood mark indicates the highest level or the flood depth. The height of the flood mark on both sides of the tree trunk is not the same. In the direction of the water flow, due to the collision of the water flow with the tree trunk and the splash creation, the height of the flood mark is higher than on the opposite side. Therefore, the height or depth of the mud (flood mark) in the opposite direction of the water flow indicates the maximum depth of the flood flow. Finally, in the riverbed and floodplain area, the flood depth and flood zone were determined in several places for the studied flood using the observed flood marks (Figure 2B–D). These data were used as important input data for the calibration and validation of the river hydraulic model.

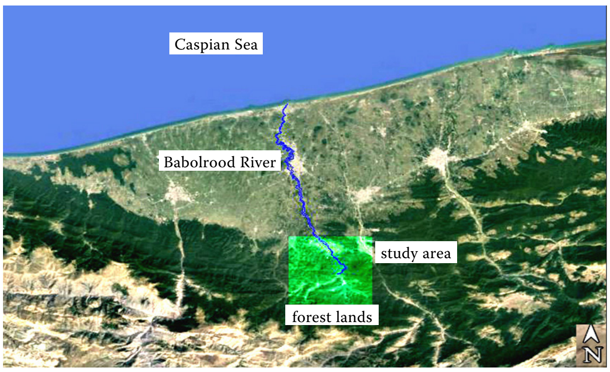

Figure 1. Location of the study area and the study river in the north of Iran (scale: 100 000)

Modelling the hydraulic behaviour of the river. At this stage, a hydraulic model was proposed to simulate the hydraulic behaviour of the river. First, the HEC-GeoRAS (GIS) extension was used to model the geometry of the riverbed and the floodplain of the river (centre streamline, banks, cross-sections) using topographic maps with a 1 : 1 000 scale. A 3D model of the river bed was simulated using the GIS and topographic map. The banks were accurately identified based on the topographic maps. Cross-sections were determined based on changes in the riverbed geometry based on field observations. Then, geometric data from the GIS to HEC-RAS model were entered and a hydraulic model for the river was presented to simulate the hydraulic behaviour of the flood (Pistocchi, Mazzoli 2002). Furthermore, Manning's roughness coefficients were determined by field observations and Cowan's method. Manning's roughness coefficient (n) includes all the factors affecting the resistance of the riverbed and canal walls against the flow and in the hydraulic calculations of the open channels, the coefficient n is usually estimated according to the condition of the study river as part of the primary data. In general, to determine and estimate the coefficient n in rivers, the river is divided into two main parts, the main canal and the floodplains of the right and left banks. In this research, Cowan's method was used to determine the roughness coefficient (Werner et al. 2005). Cowan's equation (1) is given below:

$$\mathrm{n} = (n_0 + n_1 + n_2 + n_3 + n_4) \times m_5 \quad (1)$$

where:

n_0 – base coefficient;

n_{1-4}; m_5 – correction coefficients.

n_0 is a base coefficient that is calculated according to the riverbed material and the correction co-

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Figure 2. (A) The effect of flood marks on the tree trunk; (B) flood mark (sediment) in the flood direction (flood depth) and in the opposite direction of water flow (water splash during flood occurrence); (C) flood mark and determination of flood depth in the flood plain area; (D) flood zone

efficients n_1, n_2, n_3, n_4, and m_5, respectively, include the irregular effects of the cross-section, how the cross-section changes, the presence of point bars in the riverbed, the vegetation and the meandering rate of the river.

After modelling the riverbed geometry, determining the bed roughness coefficients and the control sections (normal depth method), a mixed flow regime was considered which was implemented with a low initial discharge (Pistocchi, Mazzoli 2002; Yazdi, Salehi Neyshabouri 2015). The summary of the input data for modelling the flood depth and flood zone is given in Table 1. The results of the hydraulic model in the form of the flood flow depth and flood zone were matched with flood mark rates. To achieve the past flood discharge step by step by the trial-and-error method, we increased the discharge in a step of 10 $m^3 \cdot s^{-1}$ and compared the changes in the flood depth and flood zone with the flood mark observations. Finally, with a gradual increase in the discharge values in the model, the previous flood discharge was determined based on the flood marks until flood depth and flood zone have been achieved.

Calibration and validation of the hydraulic model. At this stage, the four-kilometre reach

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Table 1. Input data for the modeling of flood depth and flood zone

Data	Source	Method and accuracy
Topographic map	ground surveying	scale 1: 1 000
Roughness coefficients	field observation and Cowan's method	Cowan table
Flood mark height Flood zone	field measurement	accuracy of 1 mm

of the study river was divided into two categories: calibration reach and validation reach. The flood mark data in the first two kilometres of the reach were used to calibrate the model based on the changes in the discharge. After achieving the flood discharge and model calibration, the model validation was performed in the second reach (the other two kilometers). We compared the results of the calibrated model of the flow depth and flood zone parameters with the observational data of the flood marks in the second reach (Bárdossy 2007).

Flood zoning using flood marks. The flood zone is an important issue in river engineering and disaster management (Azarga 1999; Islam, Sado 2000; Hooijer et al. 2004; Balasch et al. 2011; Santos et al. 2011). The accuracy of flood zoning has always been questioned. Therefore, a method should be used to validate flood zones. In this regard, flood marks can be an effective tool to calibrate and validate flood zoning maps. However, we face two problems or limitations about flood marks: (*i*) lack of trees having the proper distribution in the riverbed and its flood plain, (*ii*) the occurrence of floods with discharges similar to other discharges considered in the flood zone. In general, flood discharges with a time return (*Tr*) of 10, 25, 50, 100, and above are considered in studies to determine the riverbed boundary, the design of structures in the riverbed and the flood zoning. Therefore, finding similar flood marks is a serious limitation in studies.

RESULTS

Based on field observations and measurements of flood marks on trees, the maximum flow depth of the past flood was estimated to be between 10 cm and about 2 m. The flood zone along the river has been highly variable due to topographic changes, and has been observed from 30 m to more than 100 m. Based on the topographic map, the geometry of the river bed and lands of the flood plain was simulated and the longitudinal profile of the river and the depth of the flood flow in the study reach of the Babolrood River are given in Figure 3.

After presenting the hydraulic model by the trial-and-error method and gradually increasing the discharge, the maximum instantaneous discharge of the last flood was estimated at 155 $m^3 \cdot s^{-1}$. Therefore, the model based on these flood marks presented a defensible discharge rate. The flood flow depth changes in the bed of the Babolrood River, based on the calibrated model, are given in Figure 4. The flood depth of the central line of the river fluctuates between 60 cm to more than 2 m. Based

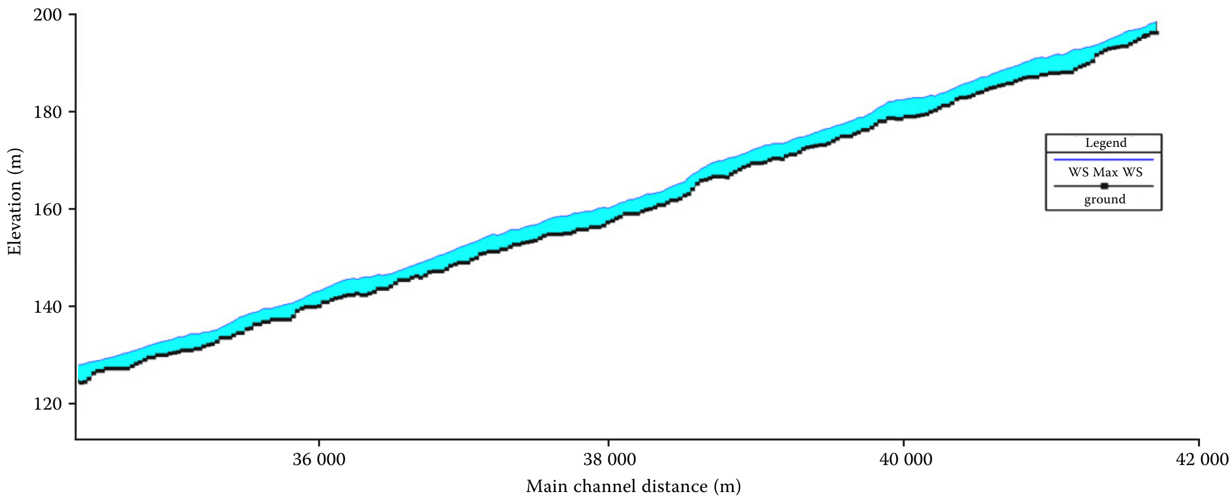

Figure 3. Longitudinal profile of the river and flood flow depth in the study reach of Babolrood River during the study flood

WS – water surface

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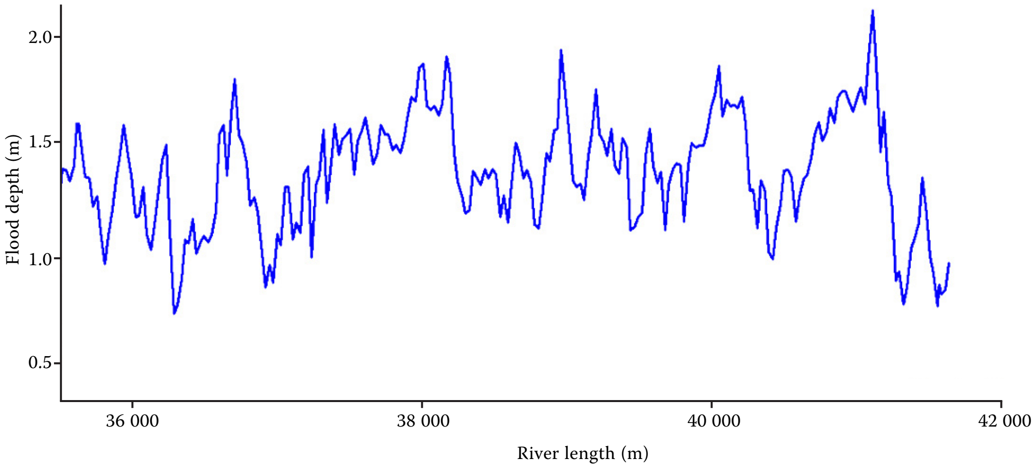

Figure 4. Changes in the flood flow depth in the study reach of Babolrood river during the study flood

on these results, there is a slight difference between the values of the maximum depth of the previous flood estimated by the model and that estimated by the flood marks. The reason for this is that the Talweg line included the deepest part of the riverbed and also showed the maximum depth, but there were no flood marks or any trees in the Talweg line. Of course, to calibrate and apply the flood marks, it is not necessary to have a tree species with observational data in the centre stream line or the Talweg line. One of the important applications of flood marks on tree trunks is the prediction of the nonlinear flow profile or flow turbulence in the hydraulic modelling. Flood flow does not have a linear flow profile, its characteristics are turbulence in the river flow and hydraulic jumps, which are clearly shown by the height of the flood marks on the trees in a section of a river. Figure 5 shows one of the cross-sections of the Babolrood River and the location of trees and flood marks to evaluate the accuracy and precision of the flood flow depth and model validation. The hydraulic model was calibrated based on the measured flood marks. Then,

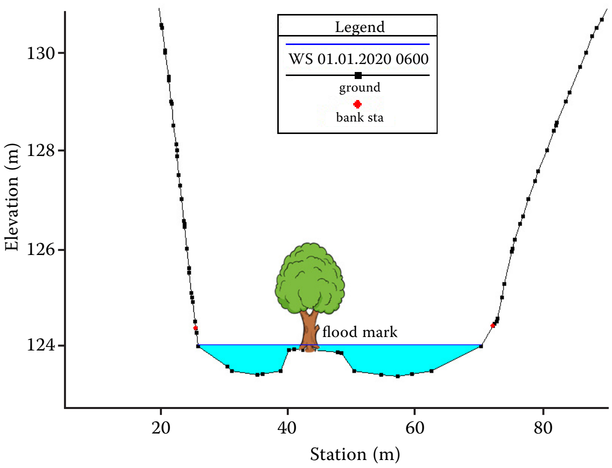

Figure 5. One of the cross-sections of Babolrood River and the location of the tree and flood mark to evaluate the accuracy of flood flow depth and validation of the hydraulic model

WS – water surface; bank sta – bank station

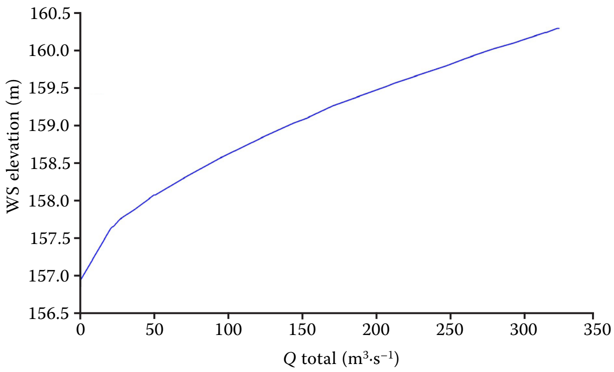

Figure 7. Water level-discharge curve of the flood flow in the study reach of Babolrood River

WS – water surface; Q – discharge

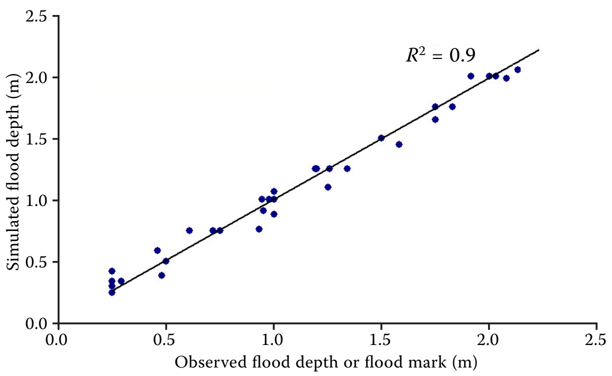

Figure 6. Validation results of the hydraulic model by comparing the flood marks depth with the predicted values of flood depth by the hydraulic model

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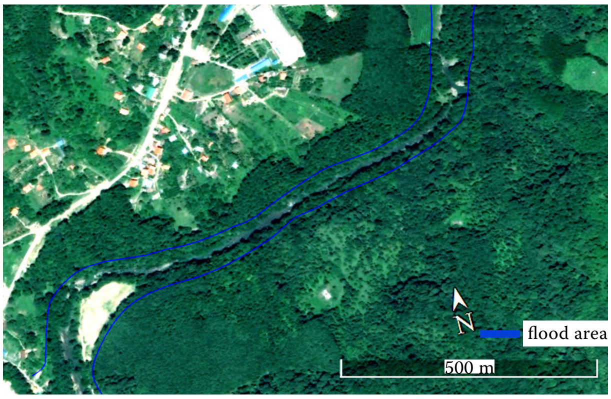

Figure 8. Determining the flood zone of the studied flood based on the results of the hydraulic model and flood marks on trees

the calibrated model was validated. A comparison between the simulated flood depth with the rates obtained from the flood marks was used to validate the model and the results are shown in Figure 6.

Based on the results of the validated model, the discharge-water level curve at the end of the study reaches of the Babolrood River is given in Figure 7. Moreover, the past flood zone was determined based on the results of the hydraulic model and flood marks on the trees and is given in Figure 8.

DISCUSSION

The results showed that the level of the maximum flood mark or mud lining on the tree trunks easily shows the maximum depth of the flood flow (Luu et al. 2018). On both sides of the floodplain, the difference between the effect of the flood marks on both sides of the flow direction and opposite to the flood flow direction is minimal. However, in the central line of the river flow, due to the higher speed and the flood depth, the turbulence and the impact of the water on the trunks of the trees creating a muddy water splash will make it a little difficult to determine the exact level of the flood depth.

Determining the flood zone based on flood marks on trees can be easily performed in conditions where a significant number of trees are scattered in the riverbed and floodplain, when the flood flow turbidity is high, which is observed in the maximum flood discharges in forest watersheds. However, access to an appropriate number of trees located in the riverbed is the main limitation in using flood marks in forest watersheds without a hydrometric station. Land use change and deforestation are among the problems of today's world, especially in Iran (Werner et al. 2005; Sheikh 2014; Worku et al. 2017; Walega, Salata 2019). To solve this problem, the discharge can be determined in the upstream reach of treeless sections based on the flood marks and then by flood routing downstream by hydrological or hydraulic methods, where discharge changes along the river route can be determined (Hirsch et al. 1990; Pappas et al. 2008).

On the other hand, the topographic conditions of rivers in mountainous areas are such that the rivers are young and have turbulent flow. Therefore, the longitudinal profile of the water surface is not linear and the flood flow is completely turbulent. It is difficult to simulate unsteady flow conditions and to use hydraulic models without any observational discharge-water level data. Therefore, the flood mark data on trees will be very useful in determining the non-linear profile of water flow during floods. The maximum instantaneous discharge rate of the last flood was estimated at 155 $m^3 \cdot s^{-1}$. This result corresponds to the flood flow depth or the height of the measured flood marks. Furthermore, flood marks on the river banks also confirm this. The measured flood mark depth was compared to the results of the validated model with the maximum flood level values. These results did not differ significantly on the banks of the river and the lands of the floodplain. However, in the centreline of the flow, there is a minimal difference, the amount of which varies in different places. The reason for this was the lack of trees in the deepest parts of the riverbed. Furthermore, the stability of the bed and severe erosion of the bed during floods are also discussed. However, no evidence or signs of severe bed erosion were observed in the study reach. In any place of the riverbed, according to the altitude of the riverbed and the height of the flood mark, the model can be calibrated or validated, and this will not affect the methodology and the results. Based on the flood mark data, the hydraulic model was calibrated and the discharge rate and flood flow depth were determined. Then, validation of the model was performed. The comparison between the predicted values of the optimised model with the observational values of the flood marks indicates the high efficiency of the model and the accurate performance of the model calibration process. Flood mark data have also been used to determine past flood zones, and based on these flood

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marks, the flood zones were easily determined in studies whose effects were consistent with the flood marks on the ground. Also, the flood zone in the hydraulic model had significant differences from the flood marks zone, which could be due to the not very high accuracy of the topographic mapping or changes in the riverbed during a flood occurrence. Finally, to determine the zone of past floods, it is possible to combine the flood zone of the hydraulic model and verify it with the effects of the flood marks if there are sufficient flood mark samples along the river and on both sides of the river.

CONCLUSION

Limitations of using hydraulic and hydrological models are their calibration and validation, and finally ensuring the accuracy of their results. The use of flood marks on tree trunks is a very efficient method to calibrate and validate these models. The distinctive feature of this method is its simplicity and it can be achieved in a short time and at a low cost. However, the limitation of this method is to find flood marks on the trees in the riverbed and floodplain. This method can be used to estimate the peak flood discharge in ungauged rivers, to verify the water flow profile and to specify the flood zone. Compared to other calibration and validation methods of hydraulic models, it is a simple method that can be used by most hydrologists and hydraulic experts. The exact determination of the height of the flood mark and identification of the flood that caused the flood mark should be considered in this method, which can be determined by the discharge data of the downstream hydrometric station or nearby rivers or from existing news and documents. Flood marks can be used to determine the riverbed boundary in forest lands in river engineering studies. Furthermore, flood marks can also be identified on the banks of the river, and the bending state of perennial herbaceous plants in a way that reflects the flood flow depth. The combined use of flood marks on trees and flood marks on river banks or signs of floods on the rangeland vegetation can remove the restrictions on the access to a large number of flood marks on trees. Finally, for future studies, we propose the use of flood marks on trees with other hydrological or hydraulic modelling methods such as rainfall-runoff models.

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