Original Article

Evaluation of the Two-Dimensional Hydraulic Model LISFLOOD-FP in Floodplain Predictions of Various Return Periods

Ehsan Fatapour[1]*, Ali Afroos [2], Babak Amin Nejad [2], Ali Saremi [2], Amir Khosrowjerdi [2]

[1]Ph.D candidate of Water Structures Engineering, Islamic Azad University, Science and Research Branch, Tehran, Iran. [2]Assistant professor of Agricultural Sciences and Food Industries Faculty, Islamic Azad university, Science and Research Branch, Tehran, Iran.

Abstract

Hydraulic models are the primary tools used to plan and develop structural and non-structural flood management and mitigation methods. The purpose of employing such tools is to simulate flood damage in a given area, depending on several flood scenarios with various intensity, duration, and return periods. Recently, raster-based hydraulic models have been considered in modeling the determination of floodplain and flood hydraulics. In this paper, a 2D hydraulic model, i.e., LISFLOOD-FP was applied to predict floodplains of various return periods over a 4.5 km reach from the Khorramabad River in Lorestan province. The model was calibrated based on a flood event using the parameters of floodplain and channel roughness coefficients against the observed floodplain depth at the hydrometric station. The roughness coefficient parameters were estimated by the calibration process to minimize the relative error (E) index between the observed floodplain depth and the predicted depth. This model was validated using two separate flood events. The relative error (E) index was 2.9% at the calibration stage and 1.7 and 15.4% at the validation stage for both flood events. Finally, the calibrated model was used to predict the floods of various return periods.

Keywords: 2D Hydraulic Model, LISFLOOD-FP, Floodplain Prediction

Introduction

Floods are costly natural disasters that can cause deaths, financial losses, and damage to communications, transportation, and critical infrastructure. Forty percent of all natural disasters worldwide and half of all deaths from natural disasters are related to floods [1]. In addition, climate change forecasts indicate that the frequency of floods may increase in the future. In response to this global disaster, the demand for better flood forecasts has increased [2]. Floodplains are very important because of the variety of sources and have always been of interest to human societies. In recent years, the growth of cities on the banks of the rivers has been increasing. The increasing population growth and the lack of attention to environmental capacities and inappropriate use of resources have led to widespread damage to these communities, which clearly demonstrates the need for management in floodplains. In flood and floodplain management plans, the first step is to prepare a flood zoning map. Applications of these maps include riverbed determination, economic study, and justification of civil engineering projects, flood forecasting, rescue operations, and flood insurance [3]. Hydraulic models are the primary tools used to plan and develop structural and non-structural flood management and mitigation methods. The purpose of such tools is to simulate flood damage in a given area, depending on several flood scenarios with various intensity, duration, and return periods [4]. Flood zoning models play an important role in flood forecasting. There is scientific interest in combining direct flood observations from remote sensing sources with these flood zoning models to improve forecasts because the number of ground-based measurement stations is low and many river basins are inaccessible to ground-based measurements. Two-dimensional floodplain modeling is one of the key components of flood risk assessment and management. Therefore, it is not surprising that there has

Address for correspondence: Ehsan Fatapour, Ph.D candidate of Water Structures Engineering, Islamic Azad University, Science and Research Branch, Tehran, Iran.
E-mail: fatapourehsan@gmail.com

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been a considerable effort over the past decades to develop algorithms of increasing complexity to simulate water flow in rivers and floodplains. Raster-based hydraulic models have been recently considered in floodplain and flood hydraulics modeling [5]. The advantages of raster-based models include simplicity of formulation, computational efficiency, and ease of use, which are one of the significant advantages for their future application and evaluation. The computational efficiency of such models means that they can be applied at a higher spatial resolution compared to more sophisticated computational techniques such as finite element method (FEM) [6, 7].

Hydraulic models are used as one-dimensional, two-dimensional and three-dimensional depending on the nature of the phenomenon:

The LISFLOOD-FP hydraulic model is a raster-based two-dimensional model for subcritical flow that solves shallow-water equations using a finite difference method (FDM) on a network. This model is based on high-resolution raster DEMs, which are dramatically available for many river floodplains. This model includes a one-dimensional kinematic wave approximation for channel flow that is solved using an FDM, which is a 2D diffusion representation of the floodplain flow [8].

There have been many studies on the application of the 2D hydraulic model LISFLOOD-FP to simulate flood flow and to provide floodplain maps [9-12]. Bates and Deero [8] used the LISFLOOD-FP model for a 35-km reach of the Meuse River in the Netherlands to simulate a large flood event that occurred in January 1995. The event was selected based on available data and aerial imagery for the floodplain to allow for appropriate model validation. DEMs were prepared at 100, 50 and 25 m resolutions. The developed model correctly predicted 81.9% of the flooded areas with the best simulation fit. Landt [13] studied the effects of various flood events, including the 100-year flooding of the Muskingum River in Ohio on the urban environment using the two-dimensional hydrodynamic model LISFLOOD-FP and prepared the urban floodplain map. The prediction results of the model showed good agreement with the observed floodplain maps and the prediction of river water surface with one-foot accuracy. Overall, the application of the LISFLOOD-FP model in various studies indicates its proper performance in floodplain predictions [14, 15]. In the field of water resources management, an important research direction is the consideration of model integration [16-18]. Many models are capable of describing specific physical processes in detail, so this draws attention to the integration of different models to develop a tool that can simulate hydrological processes with a level of consistency of details. Model integration can be a solution for managing the multidisciplinary nature of hydrology. However, this is not an easy task because most models are developed to answer one or a limited number of specific research questions. Therefore, most models lack a perspective on interoperability with other models and thus have limited potential for application in integrated systems. In addition, older codes have generally been revised several times by various researchers to improve a particular aspect (e.g., time step options, new equations, spatial resolution) regardless of the model's structure and complete equations. The result is often a very complex code, with hard maintenance and limited potential for deployment; in addition, it may run slower and be susceptible to errors and bugs.

When selecting a hydrological model for a particular study area, the specific purpose and constraints of the area must be taken into account. This particular concept is rarely used in practice, and most applications of the hydrological model belong to the category of "one model fits for all" [19]. Van Hui et al. (2014) suggest adding "flexibility in the model building process" as a possible option [20]. A flexible modular model allows for the creation of several models with different structures, which can be used to better determine sources of uncertainty than input uncertainties and parameters, namely conceptual uncertainty or model structure [21]. Fenicia et al. (2011) point out the high capability of flexible modeling frameworks in watershed hydrology. They also list a considerable number of these flexible frameworks for conceptual hydrological models, although more complex physical models have not been explored. Flexibility and ease (simplicity) in adapting models can also help reduce parameters by providing cost-effective models with varying levels of complexity [22], as well as understanding hydrological processes. Process-based models are particularly useful in that they provide outputs from different hydrological flows that can help calibrate and validate more than one variable and may provide “better predictability across a range of scales” [23]. Recent studies help identify key processes for specific watersheds [24]; process-based flexible tools can be largely useful for this type of information. Multi-model approaches have also been used in this context [25]. Furthermore, novel techniques and frameworks have been developed to evaluate the sensitivity of the model structure to select the best set of models [20] and to evaluate the realism of the model structure produced [26].

This study uses a distributed hydrological model based on WetSpa-Python physics, an object-oriented, modular, and process-based model developed based on a flexible modeling approach coded with the Python programming language, integrated with the 2D hydraulic model LIS 2FL -FP to simulate river flow and its resulting flood zoning, which can be used as a core part of a flood forecasting system. Floodplains, found mainly on farms, are threatened by river flooding due to low slope and is located by the river. Determining what area of the plain is covered by floods is important in determining floodplain damage and management and discussing flood and flood insurance. The Kashkan River, the main tributary of which is the Khorramabad River, is one of the most flood-prone rivers in Lorestan Province (Lorestan Province Regional Water Company, 2013). Appreciating it and planning hydrologic projects are some of the reasons that justify the necessity of doing this research.

This paper aims to prepare floodplains of various return periods over a 4.5 km reach from the Khorramabad River using the 2D hydraulic model LISFLOOD-FP that was used for the first time in the range. According to the model's capabilities, it shows the mass balance file in the tailwater of the model range, which includes the flooded area, water depth, and outflow discharge. It also determines the water depth and water surface elevation for each pixel at the user-specified time interval in the form of a raster network and also obtains the maximum water surface elevation and the maximum water depth predicted by the model for each pixel channel water surface profile at a user-specified time interval.

Methodology

Specifications of the Study Area

The present study was carried out over a 4.5 km reach of the Khorramabad River near the city of Khorramabad in Lorestan Province located in the Kashkan Watershed (Figure 1). The studied reach is located in a mountainous region with a moderate slope (i.e., 0.0044). Its meander ratio is 1.73. The average river width is about 50 meters and its floodplain is mainly for agricultural use. Meanwhile, the data of the hydrometric station of Cham Anjir was used at the beginning of the studied reach to determine the upstream boundary conditions of the model.

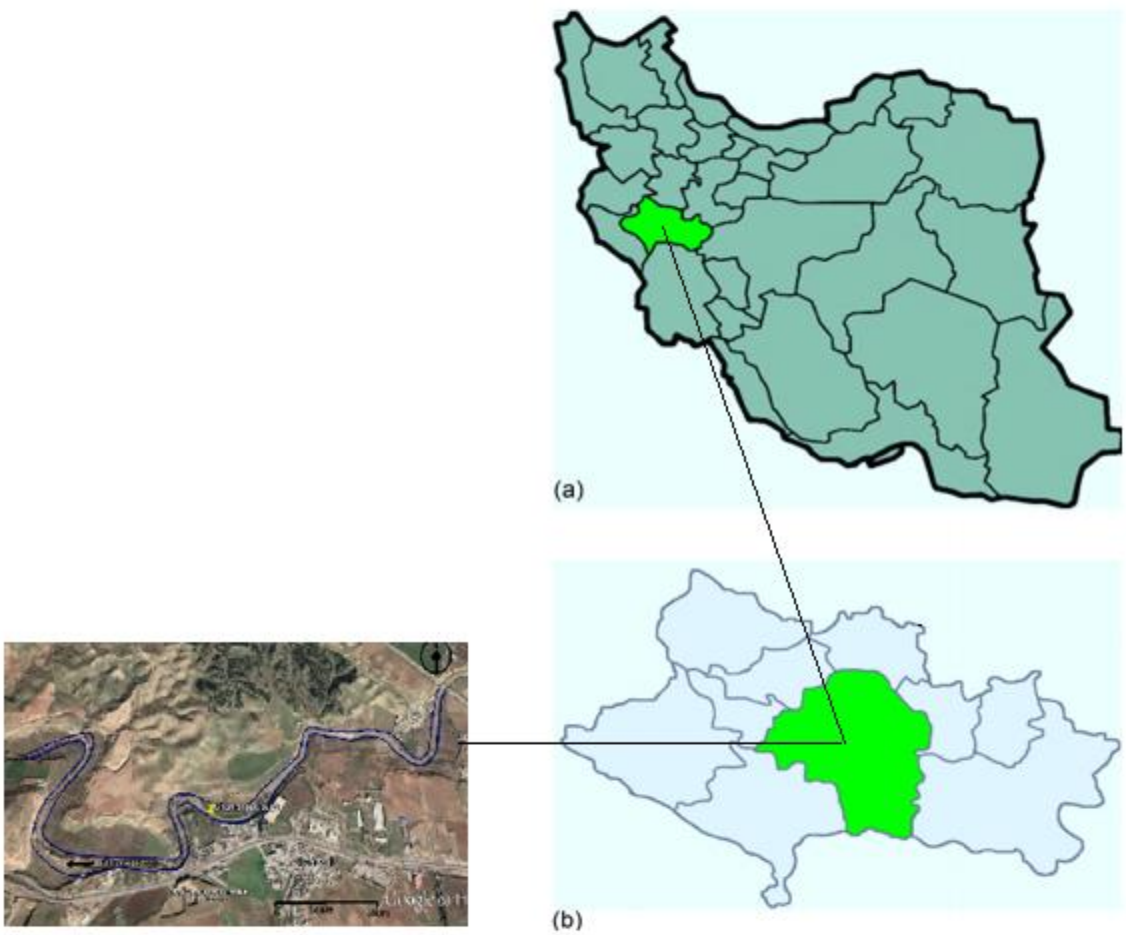

Figure 1: Location of the Study Area

The LISFLOOD-FP Model

LISFLOOD-FP is a raster-based flood inundation simulation model developed specifically to take advantage of high-resolution topographic data. The model includes a number of numerical solutions that simulate the propagation of the flood wave along the channel and passing it to the floodplain using simplified shallow-water equations. The choice of the numerical solution depends on the features of the modeled system, the time required for execution, and the available data. It calculates the model, water depth, and discharge for each time step and each cell based on the raster network used. The channel flow uses a one-dimensional method that can control the propagation of the downstream flood wave and the response to the free surface slope, which can be described by continuum and momentum equations:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \qquad (1)$$

$$S_0 - \frac{n^2 P^{\frac{4}{3}} Q^2}{A^{\frac{10}{3}}} - \frac{\partial y}{\partial x} = 0 \qquad (2)$$

Q is the volume flow rate in the channel, *A* is the flow cross-sectional area, *q* is the inflow to the channel from other sources (e.g., floodplain or channel sub-branch), *S0* is the bed slope, *n* is Manning's roughness coefficient, *P* is the flow wetted perimeter, and *h* is the flow depth. In this case, the channel is assumed to be wide and shallow; therefore, the wetted perimeter is assumed to be equivalent to the channel width. Equations 1 and 2 are discretized using finite difference and a fully implicit time-dependence method, and the resulting nonlinear system is solved by the Newton-Raphson method. Boundary conditions are provided by a flow applied upstream and a water elevation applied downstream. The channel parameters required for model implementation are channel width, bed slope, depth (to connect to floodplain flows), and Manning's roughness coefficient *n*. Channel mapping also provides bed elevation profiles that can have a slope that changes over the reach. Manning's roughness coefficient is considered as a calibration parameter.

Floodplain flows, which are similarly described through continuum and momentum equations (Equations 3 and 4), are discretized into a network of square cells that allows the model to represent the two-dimensional dynamic flow over the floodplain (Figure 2). It is assumed that the flow between the two cells is simply a function of the difference in the height of the free surface between those two cells.

$$\frac{dh^{i.j}}{dt} = \frac{Q_x^{i-1.j} - Q_x^{i.j} + Q_y^{i.j-1} - Q_y^{i.j}}{\Delta_x \Delta_y} \qquad (3)$$

$$Q_x^{i.j} = \frac{h_{flow}^{5/3}}{n} \sqrt{\frac{h^{i-1.j} - h^{i.j}}{\Delta_x}}\, \Delta_y \qquad (4)$$

where $h^{i.j}$ is the height of free water surface at node (i, j), Δ_x and Δ_y are cell dimensions, *n* is Manning's roughness coefficient for floodplain, Q_x and Q_y denote the volume flow rate between floodplain cells. Q_y is obtained similar to Equation 4. The flow depth (h_{flow}) represents the depth of water that can flow between two cells, which is the difference between the highest free water surface in the two cells and the highest bed elevation. Although this method does not accurately represent diffusion wave propagation in the floodplain due to the separation of the x and y components of the flow, it is computationally simple and presents very similar results to the finite difference discretization of the diffusion wave equation.

Equation (4) is also used to calculate the flow between channel cells and floodplain, allowing floodplain cell depths to be updated using Equation (3) in response to flow from the channel. Therefore, the model only shows the mass transfer between the channel and the floodplain and is assumed to depend only on the relative water surface elevation.

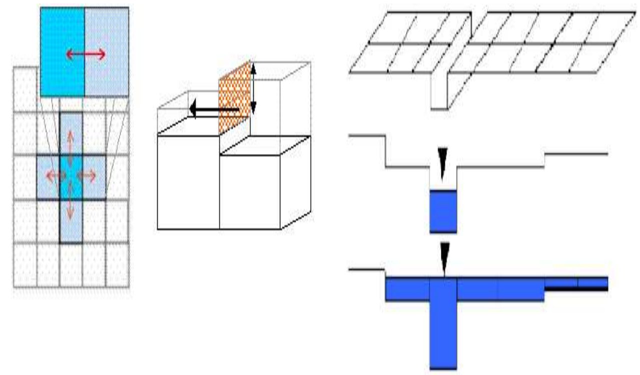

Figure 2: Flow between two cells in the LISFLOOD-FP model

- ## Model Benefits

The advantages of raster-based models include simplicity of formulation, computational efficiency, and ease of use, which is a significant advantage for their future application and evaluation.

It is assumed that the flow between the two cells is simply a function of the surface elevation difference between those two cells.

Raster-based models have recently gained popularity in floodplain inundation and flood hydraulics modeling. These models typically utilize a one-dimensional channel flow representation connected to a simple flow model between the cell networks in the floodplain. For example, the flow rate between two adjacent cells in response to a difference in water surface can be calculated by Manning's law; then, the mass conservation results in a change in the water depth of the two cells. The raster model can estimate the diffusion wave propagation in the floodplain by this innovative method. The raster-based method is simpler than the finite difference and finite element methods that help discretize and solve fluid flow equations and thus provide less computational weight and less development cost. Although they provide a raw picture of the hydraulic processes, these models have shown good results compared to more sophisticated methods; in particular, they indicate uncertainty in the model validation data. For example, compared to finite element modeling methods, they have shown acceptable results compared to remote sensing maps. The advantages of raster-based models include simplicity of formulation, computational efficiency, and ease of use, which is a significant advantage for their future application and evaluation. The computational efficiency of such models means that they can be applied at a higher spatial resolution compared to more sophisticated computational techniques such as the finite element method. A high-resolution DEM will be very useful when small-scale processes have a large impact on model predictions, for example, where the floodplain is controlled by small topographic facies such as dikes, embankments, and pits. Raster-based models may also be used to upgrade flood models because the simplicity of their computation and low memory requirements will make them used for larger ranges and domains than finite element models (typically limited to a single 60 km reach).

In general, the 2D hydraulic model LISFLOOD-FP is simple to install and operate and is computationally efficient, and can be used by various users and easily integrated with geographic information systems (GISs). The advantages of raster-based models include simplicity of formulation, computational efficiency, and ease of use, which is a significant advantage for their future application and evaluation.

It is assumed that the flow between the two cells is simply a function of the surface elevation difference between those two cells. In general, 2D hydraulic model LISFLOOD-FP is simple to install and operate and is computationally efficient, and can be used by various users and easily integrated with GISs.

The Inputs Needed to Run the Model

- ### Digital Elevation Model (DEM) of the Study Area

The DEM of the study area must be of sufficient cell size and accuracy to be able to accurately represent elevation changes and various effects of the main channel and floodplain and to include a suitable floodplain area likely to be flooded. For this purpose, the required DEM map with 10*10 cell size was extracted from an existing map at a scale of 1:1000 obtained from land (field) surveying and converted to the required format of the model using the ARC-GIS (ASCII).

Figure 3: Map of the river cross-section

- ### River Profile

The river profile file contains various cross-sections, the number of which depends on changes in river characteristics across the reach, and the coordinates, Manning's roughness coefficient, width and height of the bed for each cross-section must be determined. Due to the complexity of the studied reach and its large variations in the depth and width of the bed, 100 cross-sections were harvested to better represent the main channel (Figure 3).

- ### Floodplain Roughness Coefficient

The floodplain roughness coefficient map is a raster network with roughness coefficient values of the floodplain. The roughness coefficient depends on the height, density, distribution, and type of plants, as well as the size and shape of the channel or riverbed constituents, calculated using different methods. Roughness coefficient values, fed into the model as inputs, were determined based on-site visits and images of the riverbed and its sides according to expert views and using his experiences, whose values are presented in Table 1.

Table 1: Estimated roughness coefficient values for each river reach

Channel Roughness Coefficient	**0.039**
Floodplain Roughness Coefficient	**0.065**

- ### Definition of Boundary Conditions for Model Implementation

The upstream boundary conditions of the studied reach are defined as inflow hydrographs (i.e., unstable flow states) or fixed discharges (i.e., steady flow states). In the case of a measurement station, the downstream boundary conditions can be defined based on the downstream water surface or the output hydrograph at the end of the reach; otherwise, it can be determined based on the assumption of normal depth calculation and global reach slope determination. In the present study, based on data from the hydrometric station of Cham Anjir, a flood event with a peak discharge of 50 m^3/s was defined as the upstream boundary conditions, based on which the model was calibrated.

- ### Model Parameters File

This text file contains the information necessary to perform the simulation specifying the names and locations of the model input files, the main solution method in the channel and floodplain flow, the time step and model simulation period, defining the required outputs, and their saving location. There are three ways to solve the flow in the channel and several methods to solve it in the floodplain. The diffusive method was used to solve the flow in the channel and the acceleration method to solve it in the floodplain. Other items were identified, such as time step and others. Indeed, the flow is simulated as two-dimensional both in the channel and in the floodplain using the diffusion wave method.

After preparing the files and maps, the model was run as a program under "DOS" and its output files were obtained as Ascii, including a file related to the floodplain area and the volume of water in the user-specified time step (e.g. the following table shows part of this file and its components)

An example of a file related to discharge 552.31.

Time	Tstep	Min Tstep	Num Tstep	Area	Vol	Qin	Hds	Qout
1	1	1	1	120700	271670	552/31	2/03	127/159
100	1	1	100	404700	266990	552/31	1/044	66/404
200	1	1	200	398500	275520	552/31	0/969	59/12
300	1	1	300	388300	288060	552/31	0/895	49/491
400	1	1	400	385300	303250	552/31	0/843	43/075
500	1	1	500	385300	319970	552/31	0/81	39/105
600	1	1	600	385400	377530	552/31	0/791	36/806
700	1	1	700	388400	355520	552/31	0/782	35/482
800	1	1	800	393600	373750	552/31	0/776	34/682

In this table, Time is in seconds in which data is stored. *Tstep* is the user-specified time step (i.e., the initial time step in the adaptive model). *MinTstep* is the minimum time step calculated by the adaptive model during the simulation model, *NumTsteps* is the number of time steps since the start of the simulation. *Area* is the flooded area in m^2. *Vol* is the volume of water in the range. *Qin* is the inflow discharge in m^3/s. *Hds* is the depth of water at the tailwater output of the model range in m^3/s. *Qout* is the outflow discharge calculated at the tailwater output of the model range in m^3/s.

In the desired reach, the total optimal flooded area in the discharge entered in the model is described in Table 2.

Table 2: Floodplain area values in various inflow discharge models

Discharge (m3/s)	Floodplain Area (m2)
50.1	**229300**
72.64	**244700**
207.86	**253200**

Water Depth Files: These files contain a raster network of water depth and water surface elevation in Ascii format per cell with user-defined time intervals. This file is rastered in the Gis environment and rendered.

Model run results for discharges of 50.1, 42.64, and 207.86 m^3 show that no floodplain is created around the river with flood discharge at this discharge value, and most of the flooded area is related to the river channel itself. The following figure shows an example of a flood zoning map for discharge 50.1.

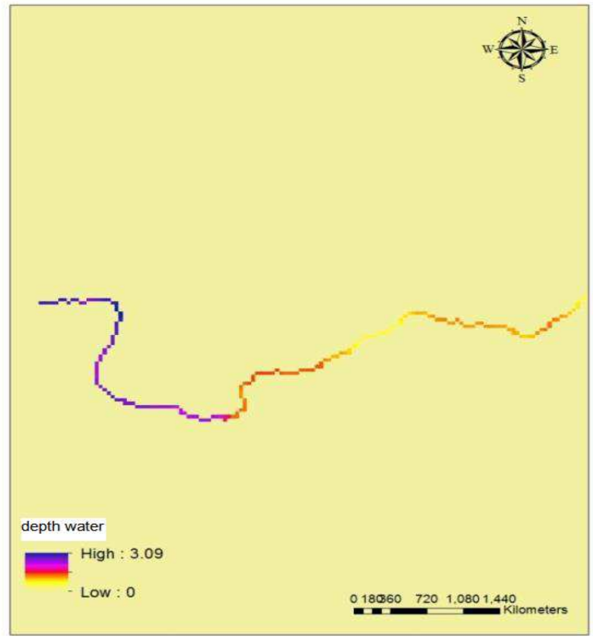

Figure 4: Area and depth of flood for discharge 50.1

The file corresponds to the time of simulation when the initial flood zone has a minimum zone per cell.

The file corresponds to the time of simulation in hours that has the maximum water depth per pixel.

The file corresponds to the time of simulation when each pixel is completely flooded.

The file corresponds to speed and discharge of water, which is an Ascii raster network of speed and discharge per pixel.

And other files that are generated by the model as needed.

All output maps are in Ascii format and can be viewed using Floodview or Floodsurf software or exported to Gis environment and rendered.

Model Outputs

The most important outputs of the model are: 1) the mass balance file, which contains the flooded area, and also shows the water depth and outflow discharge in the tailwater of the model range at the user-specified time interval; 2) the water depth and the water surface elevation for each pixel at the user-specified time interval during the simulation period in the form of a raster network; 3) maximum water surface elevation and maximum water depth predicted by the model for each pixel at the user-specified time interval during the simulation period in the form of a raster network; 4) channel water surface profiles at the user-specified time interval.

Simple applications such as Floodview and Floodsurf can be used to graphically model floodplain simulations. You can also view model output files by changing the format in the Arc-GIS environment.

Calculation of Discharges of Various Return Periods

Annual maximum instantaneous peak discharges of a 51-year statistical period (the water year 1965-66 to 2015-16) related to the Hydrometric station of Cham Anjir at the beginning of the studied reach were used to calculate discharges of various return periods. The different statistical distributions were compared using the SMADA program, and Pearson Type III Distribution showed the best fit for calculating discharges of various return periods of 25, 50, 100, and 200 years, based on the Chi-square test.

Model Evaluation

In calibrating the objective function hydraulic model, the objective was to compare the observed and simulated flood depths and to evaluate the model based on the relative error (E) index (Equation 5).

$$E = \frac{[O-M]}{O} * 100 \qquad (5)$$

where E is the relative error-index, O is the observed flood depth, and M is the simulated flood depth using the model.

Results

LISFLOOD-FP is a hybrid model that simulates one-dimensional flow within the channel as it enters the 2D floodplain. Calibration and validation are among the most important factors in applying physical and mathematical models to simulate the phenomena under study. The calibration is based on the measured information and known conditions for the nature and adaptation of the variable coefficients in the model, so that the corresponding conditions in the model are created. After calibration, the model should be validated using information not used during the calibration stage. If the models are well-calibrated and validated, the predictions made by them will be more realistic. Accordingly, after preparing the input files and data, the model was first run based on a flood event recorded at the hydrometric station of Cham Anjir at the beginning of the studied reach. The event had a peak discharge of 50 m^3/s. Initial Manning's roughness coefficient values were determined separately for the main channel and floodplain. The model was then calibrated by applying changes in floodplain and channel roughness coefficients and comparing the simulated flood depth with the observed flood depth based on the relative error (E) index. The best model fit for the E index model is 2.9%. After model calibration (indeed, determining the best Manning's roughness coefficient using a discharge of 50 m^3/s), two flood events with a peak discharge of 72 and 207 m^3/s were used to validate it, which showed the relative error (E) index 1.7 and 15.4%, respectively, that were acceptable.

After model calibration and validation, discharges of various return periods were estimated at the hydrometric station of Cham Anjir based on Pearson Type III Distribution for return periods of 25, 50, 100 and 200. After estimating discharges of various return periods, floodplain simulation was performed. They were based on a calibrated model. Table 3 shows the results for the area of simulated floodplains.

Table 3: Discharges of various return periods at the hydrometric station of Cham Anjir and their simulated zone area by the model

Return Period (year)	25	50	100	200
Flood Discharge (m3/s)	415	484	552	620
Flooded Area (m2)	539800	580900	606200	627100
Mean Depth (m)	1.26	1.53	1.73	1.90

After examining modeled floodplains in various return periods, the results appear to be good and reasonable, consistent with Rahimzadeh's (2013) results. Different models have different sensitivity with changes in friction parameters. In this study, the model used showed relatively high sensitivity to the roughness coefficient, and the resulting zones of the model changed as a result of changes in the roughness coefficient.

Since there was no flood imagery for the model output, and the only image in the historical Google Earth imagery was a flood that was only within the channel and created no zone in the plain, various discharges with water stage were used. Finally, the simulated water elevation was compared with the model of water discharge, which had negligible differences, indicating the proper performance of the model in flood optimization.

Based on the model error estimation at discharges of 50.01, 72.64, and 207.86 and comparing the water height at the station, simulated by the model, and the actual water height, it can be concluded that the model performed well in estimating water depth. Part of this difference also comes from a real or false stage. The sediments sometimes accumulate at the foot of the stage, causing the difference between the actual amount and the amount represented by the stage. To investigate the model performance for flood zoning in various return periods, the Cham Anjir Station instantaneous maximum peak discharge data were fed to Smada software for 51 years; the best statistical distribution fitted between the maximum instantaneous peak discharge data at the station is Pearson Type III. The calculated value and standard deviation were calculated based on discharges of different return periods of the probability of occurrence. In floods with return periods of 25, 50, 100 and 200 years, the probabilities of occurrence were 95, 98, 99, and 99; respectively, and calculated values were 414.86, 483.99, 552.31, and 670.18 with standard deviations of 59.35, 82.39, 108.62, and 139.309.

Finally, each of the calculated discharges in different return periods is given to the LISFLOOD model as input. After running the model, the results are given in Figure 5 for return periods of 25–200 years.

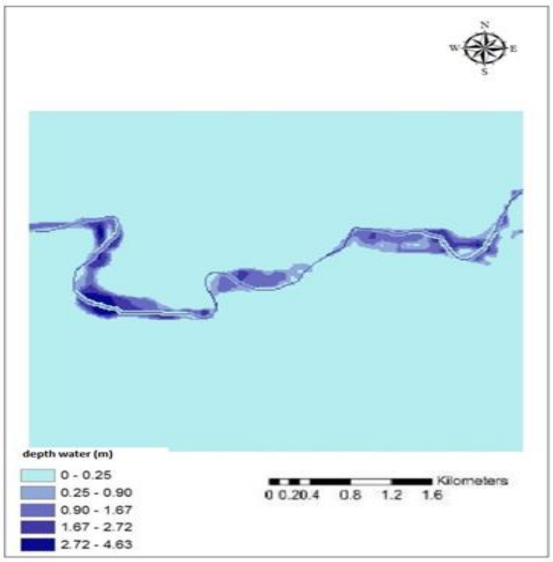

Figure 5: Floodplain and depth for a 25-year return period

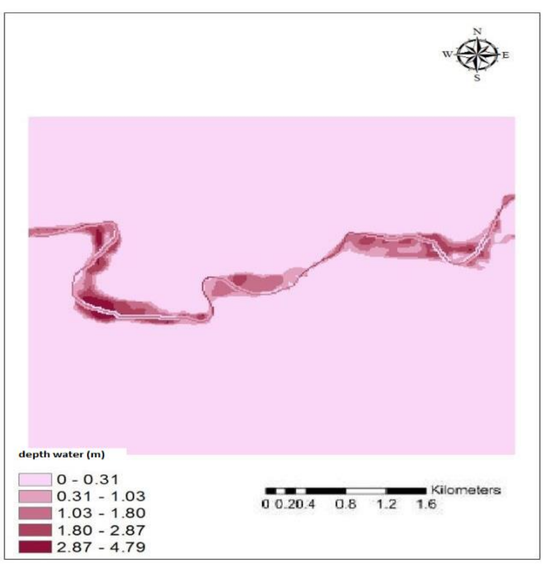

Figure 5: Floodplain and depth for a 50-year return period

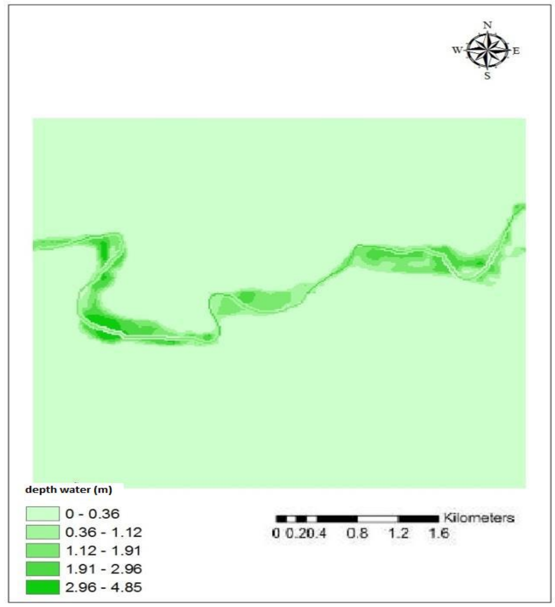

Figure 5: Floodplain and depth for a 100-year return period

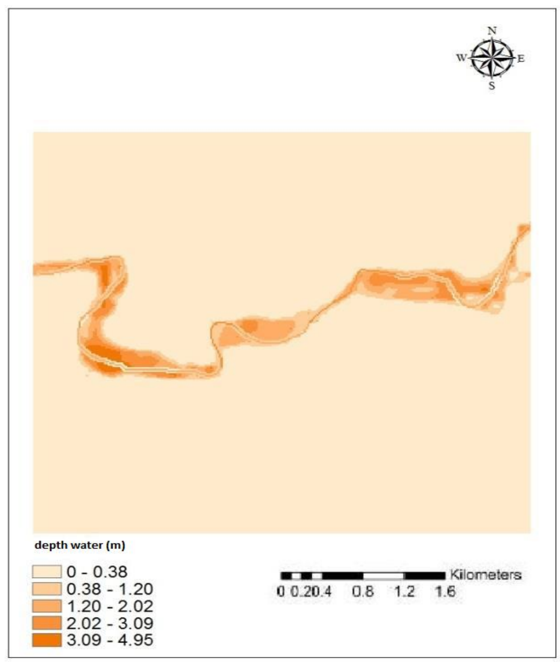

Figure 5: Floodplain and depth for a 200-year return period

By examining the floodplain maps, it was found that the natural cross-section of the river has a water holding capacity of floods of a return period of 200 years and does not cause any damage.

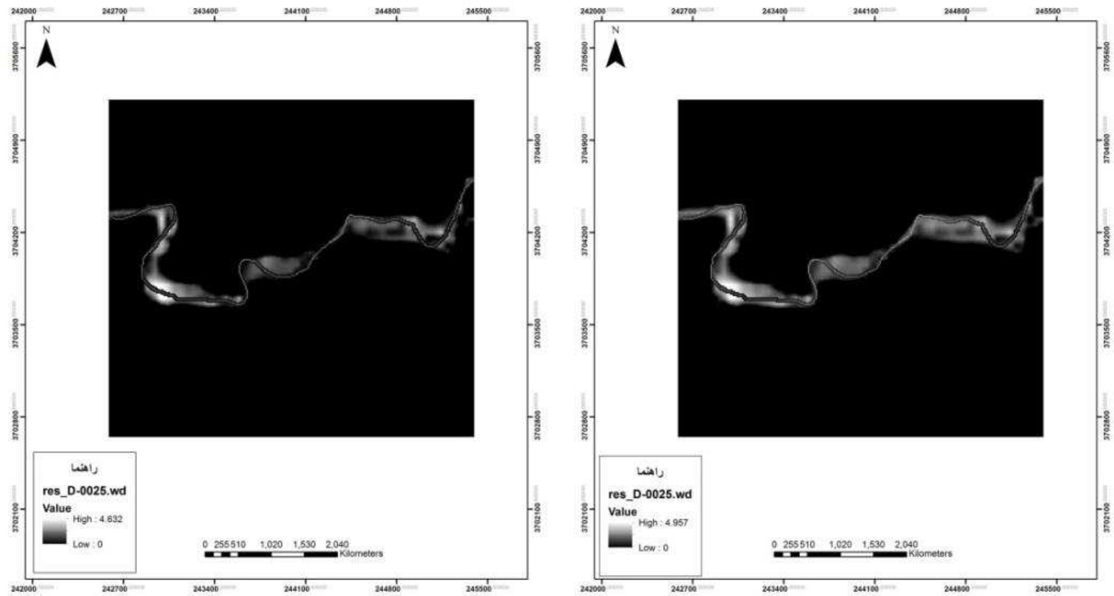

Figure 6: A comparison of flood zoning and flood depth in discharges of return periods of 25 and 200 years

Two methods are commonly used to evaluate the model.

Through the index F: $F = \frac{Num(S_{mod} \cap S_{obs})}{Num(S_{mod} \cup S_{obs})}$, where *F* is the map matching index, S_{obs} is the area (i.e., the number of cells or pixels) of the observed floodplain, and S_{mod} is the area (i.e., the number of cells or pixels) of the simulated floodplain by the model. The value of *F* varies between 0 and 100. The value of 0 is when there is no overlap between the observed and predicted floodplain by the model and the 100 represents full compliance of the observed and predicted floodplain.

Through the relative error-index E: $E = \frac{[O-M]}{O} * 100$ where *E* is the relative error-index, *O* is the observed flood depth, and *M* is the simulated flood depth. The present article used this method. Given that flood depth was used as a criterion, it has higher accuracy than the first method in which floodplain is evaluated based on satellite images. The results also confirm this.

Discussion and Conclusion

Model results for floodplain prediction with respect to the two flood events used show that the model performs well in simulating floodplain area, with E index (relative error) showing values of 1.7 and 15.4% in the validation stage for two aforementioned flood event (indeed, with accuracy and efficiency of 98.3 and 84.6). This is comparable to the results of applying the LISFLOOD-FP model at a 7 km reach by Eugene and Benefit [10] with an F index of 71% at the calibration stage and 78% at the validation stage and at 60 km reach by Horat and Bates with an efficiency index of 73% and reaches of 35 kilometers by Bates and Deero with an efficiency index of 82%. Moreover, a comparison of the floodplain area of various return periods (Table 3) shows that the floodplain catchment area should increase naturally as a result of the increased return period, such that the floodplain area with a 200-year return period is approximately 1.2 times the floodplain area with a return period of 25 years.

Hydraulic model calibration was performed by assigning different values of Manning's roughness coefficient in the channel and floodplain and based on the objective function of comparing simulated and observed floods. The calibration results showed that the model in question is more sensitive to channel roughness coefficient rather than floodplain roughness coefficient, which is consistent with the results of Horat and Bates [7].

As noted in the results section, flood discharge and alignment data were used to calibrate and evaluate the model. For this purpose, three discharges, 50.1, 72.64, and 207.86 m^3/s were used as model inputs. Then, flood zoning was done with discharges of return periods of 25, 50, 100, and 200 years. To evaluate the model performance, discharges covering most of the range of the stage-discharge curve were used, with both discharge with low return periods (2 years) and intermediate return periods (50 years) up to the number of river cross-flow discharges, which have an approximately 200-year return periods. Then, the water height of each discharge was compared with the water height of the model at the station. The error rates for each discharge were 0.06, 0.04, and 0.15, respectively, with a slight difference between them indicating the good performance of the model for the generated floodplain. After examining modeled floodplains in various return periods, the results appear to be good and reasonable.

This paper used the 2D hydraulic model LISFLOOD-FP, a raster-based model, to simulate floodplains of various return periods over a 4.5 km river reach. Due to possible errors associated with satellite imagers, flood depth, and the data used, a high degree of uncertainty can result in flood depth observations. Various work on calibration and validation of two-dimensional models of river flood inundation is mainly limited to calibrating the model against a single flood event; hence, it is a limited test of the model's predictive power. To more accurately evaluate the model's performance, the use of combined calibration and validation methods is needed to identify the weaknesses of the model. Future research priorities could be advances in model validation using more accurate data from hydrometric stations, satellite images, and aerial images. Model validation techniques using remote sensing data should be applied to reaches and other events with appropriate datasets; this will increase confidence in model predictions. In future work, we can test and compare the effect of the raster network resolutions on model performance with those obtained from other 2D hydraulic models. In general, the 2D hydraulic model LISFLOOD-FP is simple to install and operate and it is computationally efficient, and can be used by various users and easily integrated with GISs.

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