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Regional-scale flood modeling using GIS and HEC-HMS / RAS: A case study for the upper -valley of the Medjerda (Tunisia)

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Abstract : A combined hydrological and hydraulic model is presented for flood prediction in Tunisia. This model is applied to the upper-valley of the Medjerda as a test case study. Observed flows of the 2003 flood event is used for hydrological and hydraulic models, and those of the 2009 and 2012 floods events are used for validation of models. The physically based hydrologic model HEC-HMS is used to estimate the flowrate at the outlet and predicts flows accurately of the ungauged Tessa watershed which is a right bank tributary of the Medjerda river, using and calibrating the SCS-Curve Number method of runoff estimation. The HEC-RAS hydraulic model is applied to simulate flood flows and inundation levels in the downstream floodplain. The predicted flowrates of Tessa watershed are used for mapping inundations in the Jendouba-Boussalem section of the Medjerda upper-valley. All the 2D HEC-RAS numerical simulation of the 2003, 2009, 2012 flood events were performed using topographic data by inserting the DEM of the study area with 30 m resolution, soil, land use, river geometry and cross-section were obtained by combining measured survey data with cross-section delineated from the DEM.
The results of hydraulic simulation for 2003 event show a good matching with observed flowrates values. The quote part of the Tessa watershed on floods is also investigated, and shows that Tessa watershed contributes with approximatively 10% on the Medjerda River flowrates. The model may be useful in developing flood forecasting and early warning systems to mitigate losses due to flooding.

Key words: GIS, Flood modeling, Rainfall-runoff, Medjerda, HEC-RAS

1. Introduction

Flood can be considered as the most important natural disaster with an occurrence higher than any other natural hazard and affecting more people than all-natural disasters together. Due to the human interventions in natural environment and the effects of global climate change, flood hazards are occurring more and more frequently. Floods can be related to environmental issues, economic losses and social damages. Several arable land hectares get inundated, several thousands of cattle heads are drowned, crops are flooded and some cities are threatened by floodwaters in case of flooding. In Tunisia, floods are the most widespread natural hazard mainly in the Medjerda watershed (Talbi et al, 2012), especially in the Jendouba-Boussalem plain. Since the 2000’s this plain landscape has been flooded at least five time.

Flood risk assessment and management are essential step for identifying current hazards prone areas and reduce them in upcoming flood events (Ranzi at *al.*, 2011). To propose flood management measures; it is important to understand the flood and to analyze its effects based on in situ observations that are not always available, or easy to purchase. Other studies use remote sensing data for flood analysis. However, usually flood events happen during cloudy skies that limit the use of remote sensing data. Besides, flood studies based on observations are only useful for particular flood events. Hence, such observation-based maps cannot analyze future flood events or the effects on flood structural measures. The use of numerical models allows simulating flood events considering different scenarios. Hence, numerical models are significant tools for understanding flood events, flood hazard assessment and flood management planning. Many studies were carried out in Tunisia with the main objective plain protection by modeling the most important flood, using a statistics model, hydrologic model or hydraulics models (Gharbi, 2016; Talbi, 2015). Numerical models may use either one-dimensional (1D) or two-dimensional (2D) models. Although the 1D modeling approach could be useful in some contexts, mainly for artificial channels, it presents several limitations for overflow analysis (Srinivas et al, 2009). The use of 2D model is more suitable when water begins to overflow. Thus, 2D numerical models were successfully applied for flood modelling. One of the most used hydrologic/hydraulic models are the American models HEC-HMS/HEC-RAS developed by U.S Army Corps of Engineers (HEC-RAS, 2016).

The present study aims to develop a streamlined process of rainfall input and floodplain output that would enable researchers to model rainfall-runoff relations with greater efficiency, using the 2003, 2009 and 2012 events as a case study, for the Jendouba-Boussalem section from Medjerda River. One of the tributaries is ungauged, which is Wadi Tessa. Thus, the estimation of the flow at the outlet of Tessa watershed was the essential step for modeling the floodplain. This estimation was carried out using the SCS Curve-Number as a Rainfall-Runoff model. All the flood events were performed with HEC-RAS model, providing a daily simulation of the flood extent, and flow rates.

2.Methodology

2.1. Study Area

The Wadi Tessa is a right bank tributary of of the Medjerda river in the north-west of Tunisia. The watershed area is about 2500 km². The Tessa watershed is characterized by a Mediterranean climate.

The soil map shows that the Tessa watershed is occupied mainly by Lithosols and Fluviosols (28% of the total area) and Cambisols (18% of the total area). The soils complex units with undetermined spatial pattern, show variable depth and loamy texture (Regosols and Leptosols) covering 23% of the total study area (Hermassi et al., 2018).

The dominant vegetation cover are agricultural lands and forests, the land use map shows that most of the Tessa watershed surface is occupied by farmlands (70%) consisting mainly of cereals, the forests (15%) are located in the hilly zones. The rainfall is irregular; the annual average rainfall in the watershed is about 480 mm (Hermassi et al., 2018).

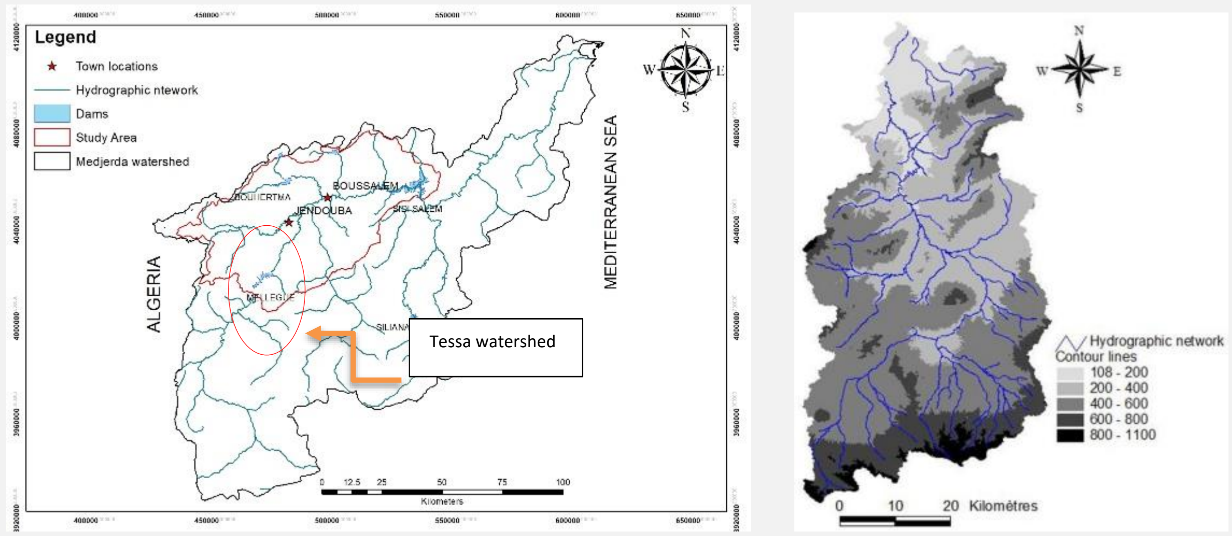


Fig.1 Location of Medjerda valley and Tessa sub-basin watershed

2.2. Rainfall–Runoff model: HEC-HMS

Runoff is modeled using the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS), developed by the US Army Corps of Engineer. It is designed to simulate the precipitation–runoff processes of dendritic watershed systems. HEC-HMS permits the modeler to choose between numerous infiltration loss parameterizations (HEC, 2000). However, only the gridded curve number (CN) technique enables spatially distributed infiltration calculations. Infiltration capacity is quantified thanks to a parameter derived by the Soil Conservation Service (SCS) called the CN. The CN is a method for determining storm runoff over an area based on land use, soil and land cover type, and hydrologic soil group (US SCS, 1986). Soil groups are determined based on type and infiltrability of a soil. The infiltration loss method is derived from a set of empirical equations that define the partitioning of rainfall into infiltration and runoff,

$$Q = (P - I_a)^2/((P - I_a) + S) \qquad (1)$$

$$I_a = 0.2S \qquad (2)$$

$$S = (1000/CN) - 10 \qquad (3)$$

Substituting Eq. (2) into Eq.(1) gives

$$Q = (P - 0.2S)^2/(P + 0.8S) \qquad (4)$$

Where:

Q=runoff; P=rainfall; S= potential maximum retention; I_a =initial abstraction; CN=runoff curve number.

Using WMS software, a geodatabase was created to contain all the mentioned data. The data were imported, merged, and clipped to the study area. The basic input in hydrologic modeling was the DEM, which was obtained from USGS database. The resulting pixel size was 30 m × 30m.

Another important input in hydrologic modeling was the land cover data, as for the soil data. The National Soil and Land Cover Datasets were created and provided by the Ministry of Agriculture. The rainfall data were represented by daily precipitations for each flood events. These data were harmonized and organized for all Medjerda basin including Tessa sub-basins. The overlay of land use maps and soil type or soil texture allows the creation of the Tessa watershed CNs. This step is performed in WMS by creating a script input file that translates the different CN values of each land use taking into consideration its relative soil texture. For the Tessa watershed, most soils are classified into Hydrologic Soil Group C, which corresponds to soils having a low infiltration rate when thoroughly wetted, often with impending layers in the soil, and CN of approximately 70-90 (Chow et al., 1988). This step will make it possible to calculate the CN for each sub-watershed, after having specified the position of the Sidi-Medien hydrometric station, which takes the values of 71.4 for upstream sub-basin and 66 for the downstream sub-basin.
This division into two sub-watersheds will subsequently allow us to calibrate and validate our hydrological model at the Sidi Medien station and to estimate the flow at the outlet level of the Tessa watershed.
Initial abstraction is a variable parameter that takes into account losses prior to the start of runoff such as interception and depression storage. Evapotranspiration losses are considered negligible for the preliminary model. Translation of excess precipitation to runoff is accomplished using the Modclarck algorithm, a version of the Clarck unit hydrograph transformation modified to accommodate spatially distributed precipitation (Clarck, 1945).

2.3. Hydraulic Model

The hydraulic model is based on HEC's River Analysis System (HEC-RAS), version 5.1 (HEC, 2016). HEC-RAS calculates two-dimensional steady and unsteady flows, and the model equations are also described by Horritt and Bates (2002). The hydraulic model requires as input the hydrograph introduced as time series data for Jendouba, Mellege, Bouhertma and the output hydrographs from HMS for Tessa watershed outlet; Its parameters are representative cross-sections for each sub-basin, including left and right bank locations, roughness coefficients (Manning's n), contraction and expansion coefficients. Roughness coefficients, which represent a surface's resistance to flow and are integral parameters for calculating water depth, were estimated by combining land use data with tables of Manning's n values such as found in HEC (2002). Due to the regional scale of the model, channel geometry was considered only for the Jendouba-Boussalem section. In order to use the RAS model to develop floodplain maps, it must be georeferenced to the basin. Hence, the DEM formed the basis for derivation of channel geometry, and was enhanced by available cross-sections.

2.4. Modeling methodology

2.4.1. Processing steps

The development of the present flood model integrates GIS with HEC-HMS rainfall-runoff model and the HEC-RAS river hydraulic model. Several previous studies demonstrate that these models provide accurate and useful results in flood related studies (Ahrens and Maidment, 1999; Anderson et al., 2002; Gharbi et al., 2013). Using a GIS tool, a geodatabase was created to enclose all of the above-mentioned data. Following data collection and processing, the stream network was delineated. An open sources GIS software called SAGAGIS executes this function through a series of steps collectively known as terrain preprocessing, implying the use of the surface topography as the origin of the stream network.
WMS GIS module also includes functionality to delineate sub-basins from the network and local topography. For calibration purposes, locations of Sidi Medien hydrometric station and the confluence point with the Medjerda River, were designated as sub-basins outlets. Fig. 1 demonstrates the preliminary drainage system delineated over the Tessa river basin.
A rainfall–runoff model simulates the runoff answer of an area to a given amount and the distribution of precipitation over a defined period. The the model output is the discharge hydrograph at each sub-basin outlet; hydrograph characteristics defines each sub-basin's unique runoff response due to differences in watershed properties including geology, geomorphology, land use and soil type effects. The creation of the rainfall–runoff model requires three files of input data: a map file, a grid cell parameter file, and a distributed model file. The map model file is a background file for spatial reference around the basin. The grid cell parameter file defines the location and properties of each cell across the basin; the modeler must first derive CNs representing each grid cell for input into this file which was used with the ModClark method of transforming rainfall to runoff. The distributed model file contains the hydrologic elements and their connectivity, and links the sub-basins to the gridded data in the grid cell parameter file.

Hydrographs results extracted from the rainfall–runoff model were saved as time series data, and inputted directly into the hydraulic model to model the extent of floodplain inundation for the Jendouba-Boussalem section of Medjerda River. The model computed an unsteady flow analysis to derive the flood polygons.
Indeed, we proceeded to the combination of the various data required by HEC-RAS which are the topographic data (DEM), geometrical data (creation of the two-dimensional flow area, mesh, land use map, roughness coefficient) and the hydraulic data (Flows recorded at the level of the stations Jendouba, Mellegue, Bouhertma and the flows calculated at the level of Tessa).

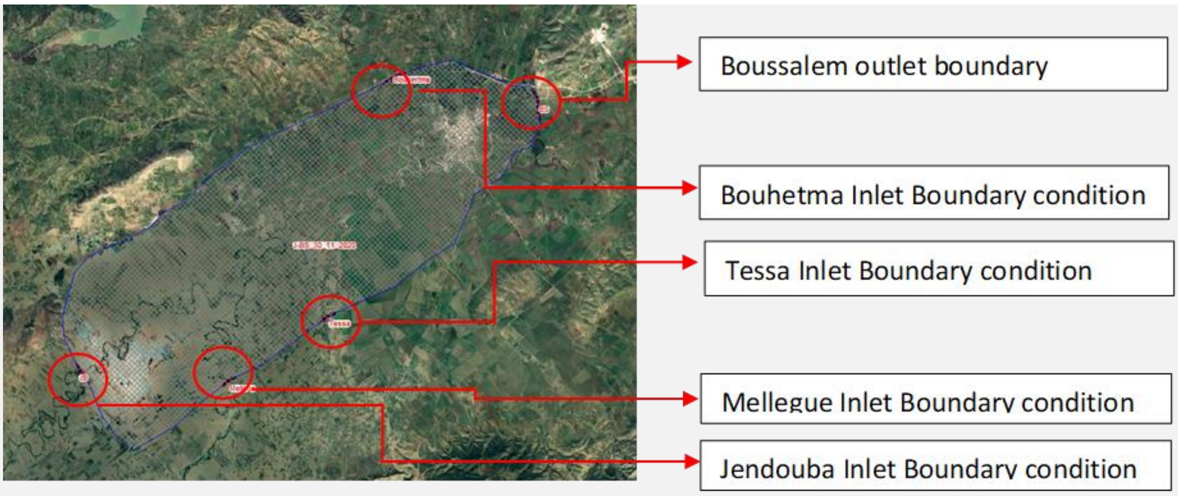


Fig. 2 Meshing of the study area and definition of boundary conditions

2.4.2. Model calibration and validation

One of the most crucial step in the creation of reliable basin representation is the calibration of the model with appropriate data. Infiltration coefficient, baseflow, and time of concentration parameters may need modification to process the best fit between observation and numerical model. Generally, the discharged output from rainfall-runoff model is calibrated with observed values. For 2003 flood event, the calibration effort produced on the hydrological model, shows a Nash efficiency coefficient (Eq.5) with 80% of efficiency (Table 1).

$$Nash = 1 - \frac{\sum_{i=1}^{n}(Q_{obs}-Q_{sim})^2}{\sum_{i=1}^{n}(Q_{obs}-\bar{Q})^2} \quad (5)$$

$$Er = \frac{(Q_{obs}-Q_{sim})}{Q_{obs}} \quad (6)$$

The hydraulic model delineating floodplain extent should be validated with an accurate image of flooding during the storm in question. Remote sensing is appreciated tool for this purpose. Numerous studies have exploited remote sensing data such as the one from Landsat Thematic Mapper (TM) to determine the extent of floodplain inundation (Ezzine 2020).
Upon completion of model improvement and test runs, the model presented in this study was calibrated in relation to measured data to evaluate its capability to reproduce flooding from the February 2003 event for the Jendouba-Boussalem section. The output from the rainfall–runoff model was used to assess the model precision of in reproducing hydrograph response. It is important to note that the calibration was performed at two scales: first, watershed parameters were modified and secondly CNs were changed at the ModClark grid cell. The 2003's flood event was used also to calibrate the hydraulic model. This model was validated for 2009 and 2012 flood events.

Table 1: Tessa watershed modeling results (Sidi Medien station)

Event	Max.Observed flow (m3/s)	Max.Simulated flow (m3/s)	Nash
2003	136.5	133.4	0.80
2009	48.7	54.8	0.64
2012	47	50.8	0.87

The comparison between the observed and simulated flows from the hydraulic model, for Boussalem hydrometric station which was set as outlet, shows a good match, but presents a relative error (Eq.6) Er = -0.0068, which indicates that the model overestimates the peak flowrate.

3. Results and discussion

3.1. Hydrological model

The hydrological result model showed a reasonable fit between model and observations; the shape of the hydrograph and the timing of the peaks matched well, although the model tended to underestimate runoff at the Sidi Medien hydrometric station. In the majority of the sub-basins, the hydrograph shape has been reproduced. Model calibration improved results by intensely increasing the volume of runoff and improving peak sharpness at most locations. The initial calibration efforts altered the CN values at the sub-basin scale and altered other parameters for each sub-basin to represent more accurately the surface runoff in the region. The simulation results for the period from January 24 to February 3, 2003 showed that the model makes it possible to accurately reproduce the flows peaks at the level of the Sidi Medien station (Fig. 2). According to Knebl (2005), the most sensitive parameters are the time of concentration of the basin, the initial abstraction (Ia), and the CN. Modifying the time of concentration improved the timing of peaks, both absolute and in relation to other peaks. Since each sub-basin has unique infiltration topography, soils, etc, Table.1 shows that for 2009 and 2012 flood events, the hydrological model presented respectively a Nash coefficient of 64% and 87%. Fig.3 shows the comparison between the observed and simulated flows for 2009 and 2012 flood events. For the calculated flow values, at the outlet of Tessa basin, which is also the point of confluence with the Medjerda river, we have peaks which values are respectively 137, 112 and 69 (m^3/s) for the flood events of, January 2003, April 2009 and February 2012 which will subsequently be injected as input data in HEC-RAS.

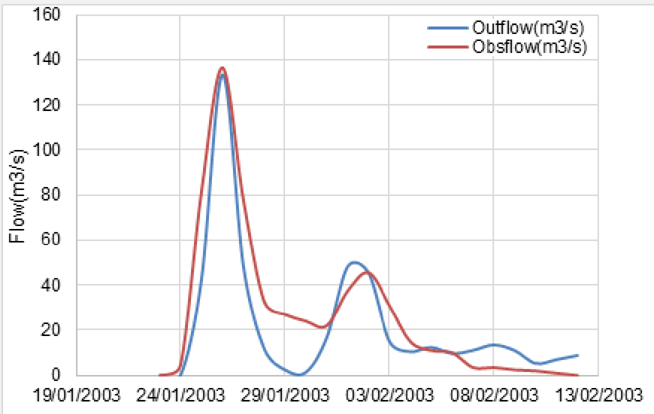


Fig. 2 Comparison between observed and simulated flows at the Sidi Medien station Flood event January 2003

The model presented in this study was calibrated against measured data to assess its ability to reproduce flooding from the January 2003 flood event. This determination involved several sets of data: The flood hydrographs produced at Boussalem gaging stations, and flood area as determined from Landsat TM satellite image data. The output from the rainfall–runoff model was used to assess the model accuracy in reproducing hydrograph response, including flood peaks. Estimated parameters were modified to produce a best-fit model. It is important to note that the calibration was performed at two scales: (1) watershed parameters such as roughness coefficients (Manning's n), which represent a surface resistance to flow and are integral parameters for calculating water depth, were estimated by combining land use data with tables of Manning's n values such as that found in (HEC-RAS, 2016), were modified at the sub-basin scale and (2) CNs values were modified.

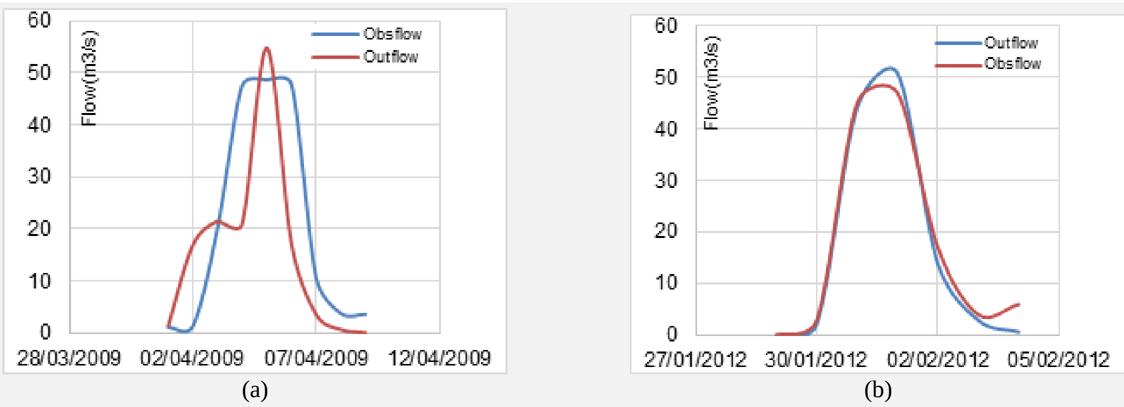
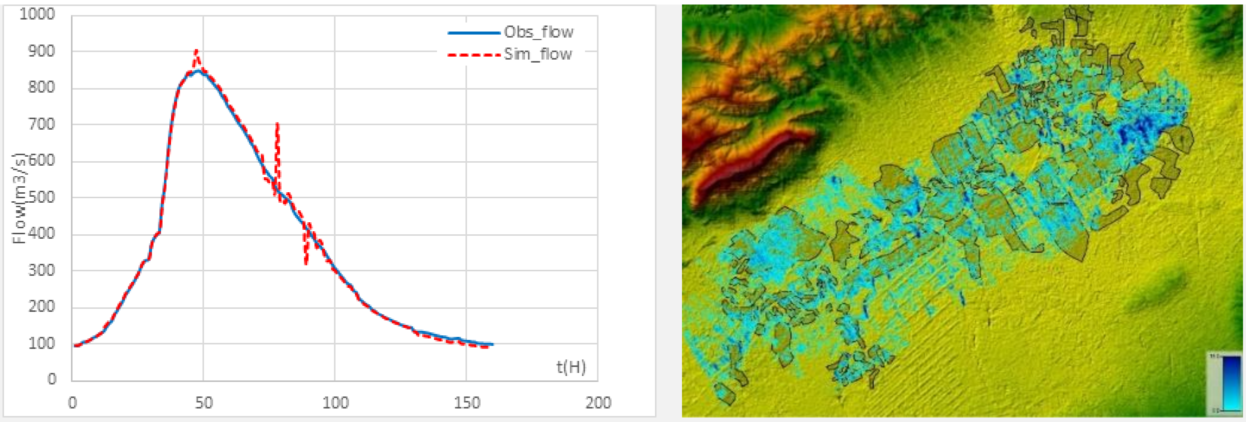


Fig. 3 Comparison between observed and simulated flows at the Sidi Medien station :(a) April 2009, (b) Febrery 2012

3.2. Hydraulic model

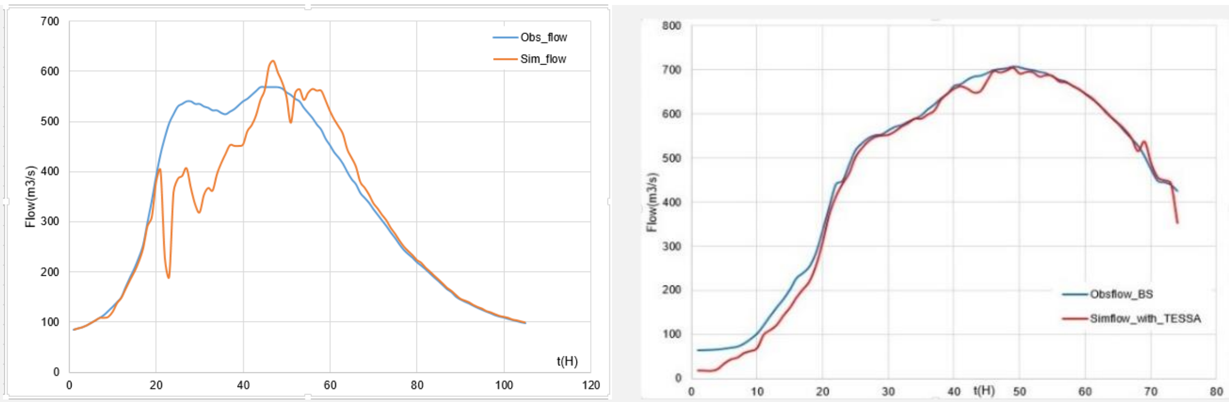
The event of January 2003 was chosen as a validation event since we have flow data recorded at the Boussalem station. The value of the roughness coefficient (Manning's coefficient) varies between 0.025 and 0.16.

The results of this hydraulic study consist in comparing the recorded and simulated flows at the Boussalem Bridge station. This comparison showed a perfect concordance between the observed and simulated hydrographs. However, we noticed a difference in the point flow rate, as the hydraulic simulations under HEC-RAS gives a peak flow rate of 907 m^3/s, whereas the observed flow rate was 849 m^3/s (Fig.5). The first output of the model consists of flood polygons showing inundated areas over the Jendouba-Boussalem section of Medjerda River. The flood polygons display the simulation output from Febrary 3, 2003 (day 11 of the flood event). This day was chosen to compare the simulation results to the available Landsat TM satellite image data during the event. The processed Landsat image result was converted to a vector shapefile and overlain on the simulated flood polygon. The comparison between the areas affected by the flood and the results presented by the different simulations of this event showed that the model overestimates flooding where the outlet of Tessa basin was assigned as inlet boundary condition for the hydraulic model.



(a) (b)

Fig.5 Simulation of the January 2003 flood at the Boussalem station



(a) (b)

Fig.6 Comparison between simulated and observed flows at the Boussalem station (a) 2009 flood event (b) 2012 flood event

The second part of this hydraulic study consists in determining the Tessa watershed contribution in terms of flow, on the Medjerda (Jendouba-Boussalem section) upper valley floods of. Therefore, the income flows from the Tessa watershed have been set to zero (0 m3/s) for all the flood events and we used the same simulations while keeping the same boundary conditions as well as the same specificities of the study area. These simulations have shown that the simulated peak flow is 772 m^3/s (Fig.7) for 2003 flood event. Analyzing also the flowrate for 2009 and 2012 flood event, Table.2 presents the comparison between the simulated peak flow without the Tessa watershed contribution and the peak flow observed at Boussalem hydrometric station. This comparison shows that Teassa watershed contribution is about 10% on the Medjerda River. The simulated hydrograph for Boussalem station for 2009 and 2012 flood events are shown on Fig.8.

Table 2. Tessa watershed contribution on Medjerda behavior (Boussalem Station)

Event	Max. Observed flow (m^3/s)	Max. Simulated flow (m^3/s)	Max. contribution	% of contribution
2003	849	772	77	9.06
2009	567.7	491.8	75.9	13.36
2012	708	667.2	40.8	5.76

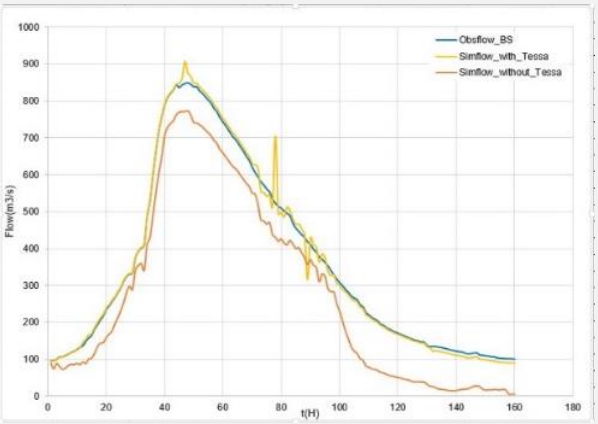
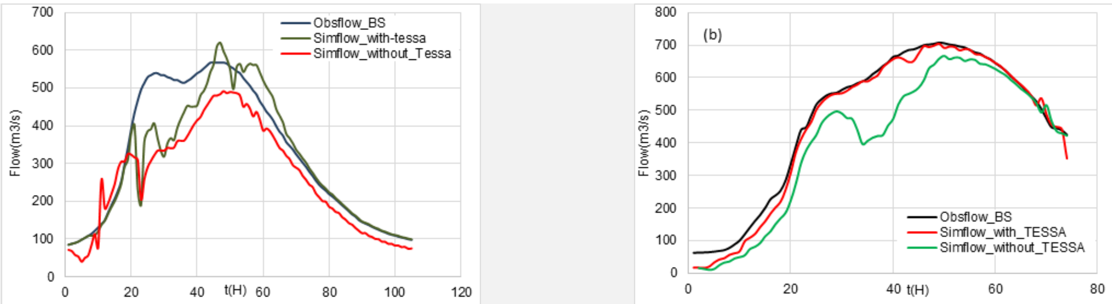


Fig.7 Comparison between the simulated flows (with / without the BV Tessa contribution) and the flows recorded at the Boussalem station 2003 flood event



(a) (b)

Fig.8 Comparison between the simulated flows (with / without the BV Tessa contribution) and the flows recorded at the Boussalem station (a) 2009 flood event (b) 2012 flood event

4. Conclusion

It is clear from the calculated hydrographs that the Tessa watershed shows a degree of harmony or consistency between the modeled and observed flow, but also represents a slight shift in the flow peak appearance which can have several explanations. The most sensitive parameters turned out to be the concentration time of the basin, the initial sample (Ia) and the CN, and the concentration time modification makes it possible to improve the peaks synchronization the, at the absolute times and relative to other peaks. The final model output consists of flood polygons showing inundated areas over the basin. Results from the Landsat analysis demonstrate that the model underestimates flooding with respect to the Landsat data. This study presents a methodology and the development of a model for determining the discharge at the outlet of an ungauged watershed that can be incorporated both in regional hydrological studies and/or in a water regional alert system for hazard mitigation. The current model will have the capacity to perform hydrological studies on a regional scale and may be incorporated or provide boundary conditions for local models.

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