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Comparison of 1D and 2D Hydraulic Models for Floods Simulation on the Medjerda Riverin Tunisia

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Abstract
In Tunisia, especially in the Medjerda watershed the recurring of floods is becoming more frequent. The purpose is to improve the different methods of hydraulic modelling, mainly regarding the floodplain modelling. Thus, weare interested in hydraulic modelling applied to the Medjerda River. Two types of models are examined in this paper; one-dimensional models using HEC RAS (1D) and MIKE 11 (1D), and a two-dimensional one using TELEMAC 2D. These models arecalibrated on data measured during the spectacular flood occurred in January 2003 in Tunisia; and a comparison of the simulation results of these 1D and 2D modelsisperformed. The objective of these comparisons is to showthe benefits and limitations of tested models in flood forecasting. The analysis of the results shows a good agreement between 1D and 2D models and that the reliability of results depends strongly on the accuracy of available data.

Keywords: Medjerda, Floods, Hydrodynamics, Hydraulic Models, 1D and 2D Modelling

1. Introduction
Due to the recurrent occurrence of major floods around the world, especially in Tunisia, several alerts methods have been developed to reduce the risk and damage. In this context, hydraulic modelling can certainly provide reliable and accurate results especially when these models can exploit the extensive information provided nowadays [1]. In this study, we are interested in modelling the dynamic of Medjerda River in Tunisia using numerical analysis of theoretical models. The aims are to delineating floodplains, and identify risk areas [2]. Hydraulic modelling consists in simulating the rivers flows. To this end, there are several types of hydraulic modelling: 1D, 2D and 3D. In this work, we were interested in the implementation of a 2D hydraulic model for simulating flash floods over the Medjerda River by using advanced modelling tools. Two-dimensional modelling is designed to complete and to improveone-dimensional hydraulic modelling that was performed in the first part of this study for simulating floods at the middle valley of the Medjerda [3]. For this, we used the TELEMAC 2D code to develop a 2D hydraulic model able to interpret the Medjerda behaviour during floods. The two-dimensional modelling includes a significant improvement in calculating hydraulic variables and also the delineation of flood zones. The main goal of this study is to analyse the hydrodynamic behaviour of the Medjerda during the spectacular flood of January 2003. In the first part, we focus on the presentation of the study area and the available data for the establishment of the hydraulic model [3]. In the second part, we present the simulation results of 1D and 2D models. In the third part, we carried out a comparative study of 1D and 2D models used to help flood risk assessment in the Medjerda. The aim is to determine the benefits and limitations of 1D and 2D models.

2. Materials and methods
Because it controls the essential element of life, fluvial hydraulic is one of the oldest sciences explored by human [4]. Fluvial hydraulic concerns the study of stream flows in natural or artificial open channels. It appears fundamental for the design, planning and flow propagation in river and the delineation of the floodplains.
The hydraulic modelling can solve this problem in order to limit harmful environmental effects of flooding. Typically, there are three types of modelling, one-dimensional, two-dimensional, and three-dimensional. One-

dimensional model will consider flow in one dimension (unidirectional). Two and three dimensional modelling allows the numerical simulation to take account to the expansion of the river in two or three dimensions respectively.
Our approach to study the Medjerda hydrodynamic is to apply numerical models in order to describe the Medjerda behaviour during floods. The used equations may be the Navier Stokes equations or the Saint Venant ones. In fact, the reality is much more complex where the situations encountered can present slope and Froude number that are not respected [5], complex bed slopes and so the flow can no longer be regarded as one-dimensional, but two-dimensional or may be three-dimensional, also the flow can be not gradually varied due to the presence of obstacles [6], slope failures, etc…
In this study, we considered initially the 1D hydraulic model already established for simulating the evolution of the water level profiles during floods. In a second step, we built 2D hydraulic model to show hydraulic parameters variations in time and space. But, before proceeding to the development of models, it's useful to give a brief description of the used equations and numerical methods for their solution.

2.1. *2D hydraulic model*
The flow in rivers was described for the first time by Saint Venant in 1871. From Reynolds equations (3D) to Saint Venant equations (2D), it is assumed that vertical velocities are almost zero and the variables can be integrated vertically [7]. The 2D Saint Venant equations are written in the following form:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \qquad (1)$$

$$\frac{\partial (hu)}{\partial t} + \frac{\partial (hu^2)}{\partial x} + \frac{\partial (huv)}{\partial y} = -hg\frac{\partial Z_s}{\partial x} + \frac{\tau_{xx}}{\rho} + F_x \qquad (2)$$

$$\frac{\partial (hv)}{\partial t} + \frac{\partial (huv)}{\partial x} + \frac{\partial (hv^2)}{\partial y} = -gh\frac{\partial Z_s}{\partial y} + \frac{\tau_{yy}}{\rho} + F_y \qquad (3)$$

Where x and y are the horizontal Cartesian coordinates; h is the water depth; u and v are the depth-averaged flow velocities in x and y directions; Z_s is the water surface elevation; g is the gravitational acceleration; ρ is the density of water; τ_{xx} and τ_{yy} are the depth-averaged turbulent stresses, F_x and F_y are the Coriolis forces. The turbulent stresses τ_{ij} are calculated with the classical k-ε turbulence model [8], which employs the eddy viscosity.

$$\tau_{ij} = v_t\left(\frac{\partial u_i}{\partial x_j}\right) \quad i=1,2 \quad j=1,2 \qquad (4) \qquad \text{Where} \qquad \nu_t = \frac{C_\mu k^2}{\varepsilon} \qquad (5)$$

Where: k is the turbulent kinetic energy; ε is dissipation rate; ν_t is the eddy viscosity.

2.2. *1D hydraulic model*
For the 1D Saint Venant model, we assumed that there is a singlepreferred direction and that flow varies slowly in the cross section of the river. Using these simplifying assumptions, the1D Saint Venant equations are obtained after integration over the river cross section [9], that is

$$\frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad (6)$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + g\frac{\partial h}{\partial x} = g(I - J) \qquad (7)$$

Where I is the bed slope, and J is the energy slope given by the following relationship:

$$J = \frac{U^2}{K_s^2 R_h^{4/3}} \qquad (8)$$

Where R_h= the hydraulic radius; K_s = Strickler coefficient
We used the Manning Strickler formula to show the bottom roughness through the coefficient (K_s). This roughness coefficient K_s requires special attention, since it will be a calibration parameter. The Saint Venant equations can be solved by numerical methods [10], namely, finite difference method which is used by the code HEC RAS and MIKE 11, and finite element method which are used by TELEMAC system.

3. Presentation of the study area

The Medjerda is a river in North Africa flowing from northeast Algeria through Tunisia before emptying into the Mediterranean Sea. It is the longest river of Tunisia stretched over 450 km, and the only permanent river in the country [11]. The Medjerda watershed is entirely located in the semiarid bioclimatic stages where the average annual precipitation is about 400 – 600 mm.Despite the relatively low rainfall in the Medjerda during the autumn and spring, severe flooding can occasionally occur during these seasons (Figure 1).

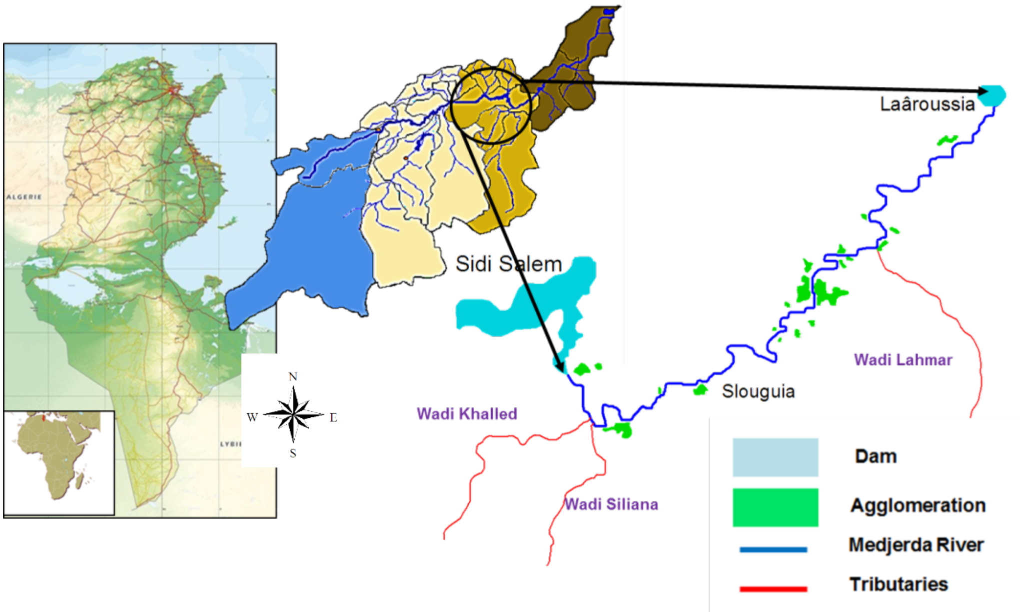


Figure 1: Location of the study area: The middle valley of the Medjerda river, Tunisia

In this research, we limit our study area to the middle valley of Medjerda, which was flooded at least three times in these last year [11]. We will pay a particular attention to the reach located between the two dams of Sidi Salem and Laâroussia [3]. This reach is extended over 85 km; it is powered by three tributaries: Wadi Khaled, Wadi Siliana and Wadi Lahmar at the right bank.
The implementation of a 2D model for the total river,to calculate the various hydraulic parameters through the extent of the study area (85 km), is very difficult to deal with. Therefore,a portion of about 20 km of the Medjerda from Sidi Salem dam until the first measurement station of Slouguia is considered (Figure 1).

4. Materials and methods

For the implementation of both 1D and 2D hydraulic models, we opted for HEC RAS and MIKE 11 software to perform one-dimensional hydraulic modelling (1D) and TELEMAC for 2D hydraulic model [12].
HEC RAS and MIKE 11 software allow us to perform one-dimensional steady and unsteady flow river. They solve Saint 1D Venant equations to predict flood routing of the rivers. They are used in several hydraulic studies such as river analysis components, flood prevention, etc...
TELEMAC 2D is an ideal modelling framework for rivers due to its finite element grid which allows graded mesh resolution. In fact, areas that require high bathymetric accuracy such as meandering can be wellhandled by TELEMAC 2D [13]. This model performs 2D hydraulic calculations; it solves Saint Venant equations of momentum and continuity, derived from the Navier Stokes equations by taking the vertical average. The main resultsare the water depth and the average vertical velocity at each point of the resolution mesh.

4.1. *Hydraulic model implementation*

When there is an overflow, there is no longer a preferred axis of flow, as should be the case in one-dimensional modelling (longitudinal axis). This imposes us to move to a two-dimensional modelling, based on the same assumptions, except that of the stream direction, based on the two-dimensional Saint Venant equations [14].
The two-dimensional hydrodynamic modelling is a tool for the representation of the evolution of flows during an event.The hydrodynamic term means that the flow characteristics (water depth and velocity) are determined at every moment of the simulated event. The two-dimensional term means that the model provides the velocities

of the water column displacement in space [15, 16]. At each calculation point and for each time of the stimulated event, the water level and the velocity are determined by calculation. It should be noted that the construction of a 2D model requires more time and highly technical skills than the case of a 1D [17].
The purpose of modelling in two dimensions is to complete and improveone-dimensional hydraulic modelling performed in a previous work [2]. The first step is to collect or acquire all necessary data for the development of the hydraulic model, as well as its implementation. The data set (topographical and meteorological data) allows us to better understanding of theflood phenomena [18].
The topographic data (cross sections, the slope map, digital model elevation (DEM), etc...) are collected from the topographical campaign realized in 2003 by the Ministry of Agriculture and Water Resources [3].Figure 2shows us the digital elevation model that we established from assembling the topographic maps 1:25000 where the contours are spaced 5 m (high accuracy).

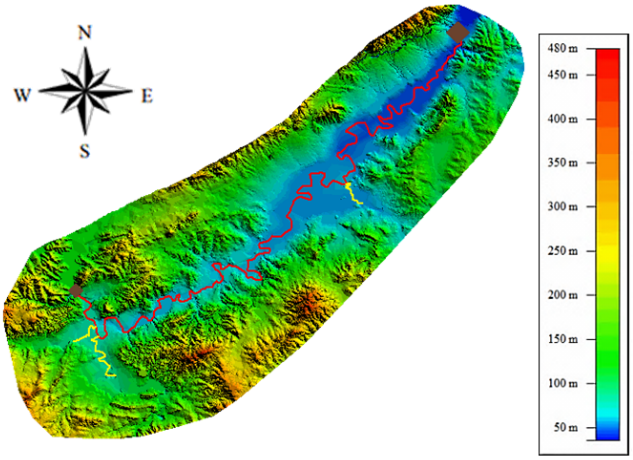


Figure 2: Digital model elevation of the middle valley of the Medjerda river

The definition of the geometry of river channels is a fundamental step in hydraulic modelling. The river topography and hydraulic structures have a major impact on the simulated water levels. This step requires a good knowledge of areas and flows in order to consider all the existing hydraulic structures while simplifying the topography to limit the number of calculation points [8]. In 1D models, topography is defined by cross sections which generate a precise definition of river bed but a rude definition of the floodplain [19]. In 2D models, the mesh provides information about the river topography. This kind of information is used to define very precisely the topography of the floodplain [12]. Thus, it is certain that more we have high accuracy data; more we can get a model estimates closer to reality.
Once all necessary information are provided, we move to the definition of the river geometry (Figure 3).

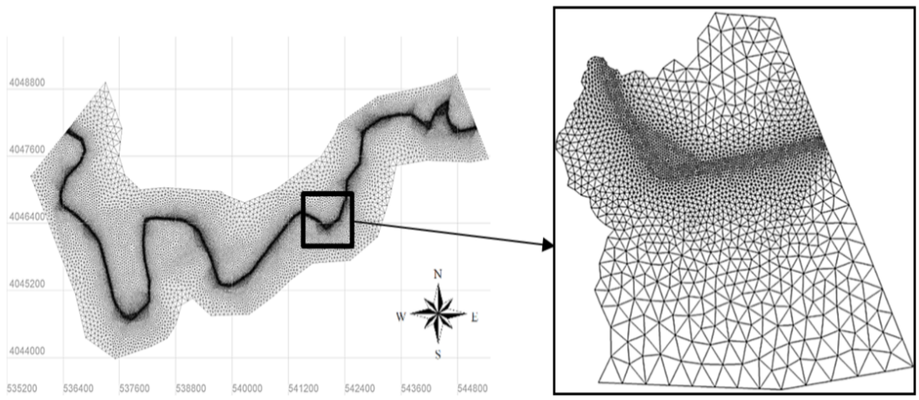


Figure 3: Mesh resolution used for the middle valley of the Medjerda, flood 2003.

The mesh size is very important in the model definition, so it's crucial that the mesh integrates and represents as faithfully as possible the reality. The choice of the mesh size is a compromise between the model accuracy, the problem of stability, and the time calculations. In this research, the mesh was carried out under Matisse;

software included in TELEMAC system. In order to better capture some of the detail in the channel bed surface, the density of the mesh was increased in the bed river (Figure 4). Therefore, we choose the spatial mesh size l = 5 m in the river bed and an unstructured mesh of the floodplain of about 50 m [20]. The Figure 4shows the established bathymetry composed of 51145 nodes.

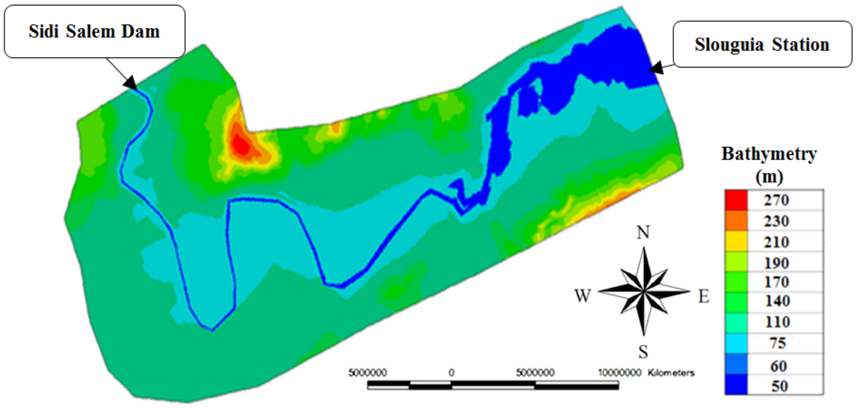


Figure 4: Bathymetry of the middle valley of Medjerda, flood 2003.

Once the mesh is completed, we proceed to the definition of the simulation parameters such as the bottom friction. Thus, we considered the same Strickler coefficient K_s=25 $m^{1/3}$/sused in the 1D calibrated model. The last step consists in the insertion of boundary conditions. These include two liquid boundaries. On upstream side we considered a flow hydrograph measured each hour during the flood of January 2003. In the downstream side, was introduced the rating curve h (Q) for the same flood. It is noted that there are many modellingconstraints [21], such as the study area has a flat terrain particularly in the river floodplain and the river network has several meanders with very low slopes and high roughness...

4.2. *Model calibration and validation*
This section describes the proposed calibration methodology. In fact, the model calibration intends to determine, from a limited number of events, the control parameter of hydraulic modelling. Regarding the calibrations of the tested models, we used for both 1D and 2D models the spectacular flood occurred in January 2003 at the middle valley of the Medjerda, in order to reproduce the flow characteristics at the river outlet. Several parameters are used in the calibration of the hydraulic model [22]. The Figure 5 below presents the measured hydrographs of the flood of 2003 for several measurement stations.

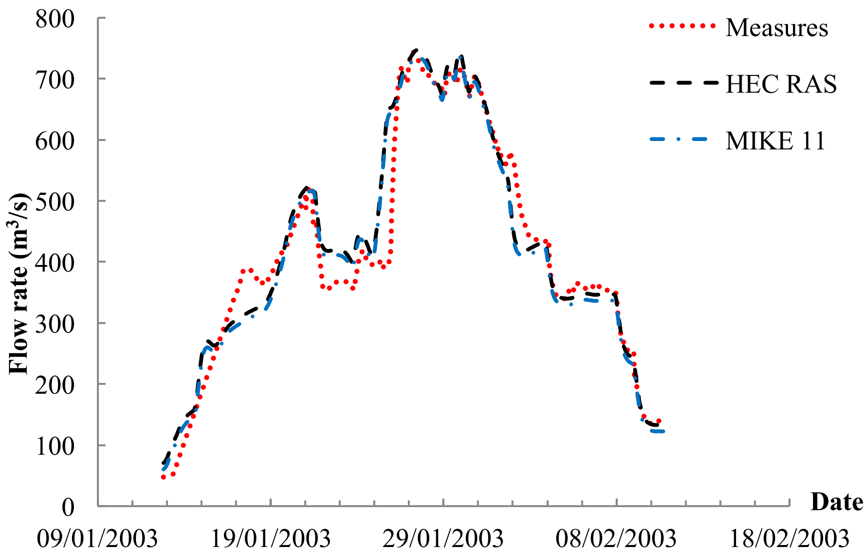


Figure 5: Observed hydrographs at the Sidi Salem dam, Slouguia Station, and Siliana, flood 2003.

Concerning the sensitivity analysis, it allows us to observe the real impact of the considered parameter and thus to define utility of using this parameter for the model calibration and validation. For our case study, several sensitivity tests were performed on both HEC RAS (1D) and TELEMAC 2D models. The roughness is the most important parameter, and so the sensitivity tests were focused on this parameter. The coefficient of Strickler 'K_s' has been adjusted to represent the role of the bottom nature (gravel, sand, silt...) and the land use (urban, forests ...) on flow dynamics [23].
The Strickler parameter has a great influence on the water level variation in rivers. Several simulation tests were carried out, by varying roughness. We retained $K_s = 25\ m^{1/3}/s$, which represents relatively a high roughness. In fact, this may be justified by the dominance of vegetation in the banks and bed river. We also note that the hydraulic model is sensitive to the roughness variation; the analysis shows that a decrease of 1 $m^{1/3}/s$ in the Stickler coefficient causes an increase of about 8 cm in the water depth.

5. Results and discussion

The current part is devoted to the presentation and analysis of simulation results. First, we start by checking the reliability of the topographic data insertion into the 1D and 2D hydraulic models. So, comparative studies were carried out between extracted profiles from the hydraulic models and those measured during the topographic study conducted in 2003. Second, we present some results performed with HEC RAS (1D), MIKE 11 (1D), and TELEMAC 2D, in particular the water depth, the velocities fields (u, v), etc… The last part is dedicated to a comparative study between water levels and flood maps forecasted by the 1D and 2D hydraulic models. The aim is to determine the benefits and limitations of the 1D and 2D models and propose eventually the most suitable software for accurate modelling for the Medjerdariver.

5.1.*Flow flood hydrograph*

To validate 1D hydraulic models, we conducted a comparative study between the simulated hydrograph by HEC RAS (1D), MIKE 11 (1D) and the measured hydrograph during the flood of January 2003 at the Slouguia station (Figure 6).

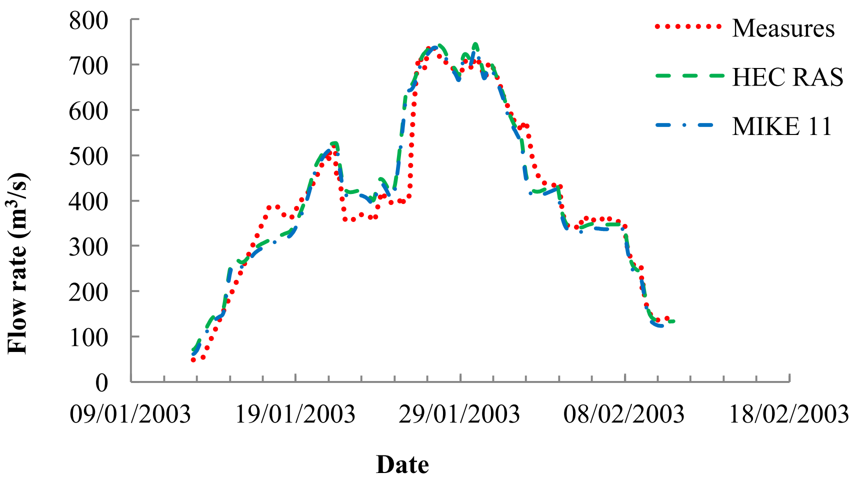


Figure 6: Comparison between the flow flood hydrographs simulated by the different models at the Medjerda, flood 2003.

To better visualize the correlation between the observed and simulated variables, we opted for two evaluation criteria [25]. The first one is the Nash criterion, used to judge the significance of the difference between observed and simulated discharges. It is between -∞ and 1, a unit value corresponds to a perfect correlation between the observed and simulated values. The second is the volume balance; this volume represents the amount of water that has passed during the flood over a time interval Δt.
We first note that the hydrograph dynamics are fairly well respected; and the hydrograph peaks are perfectly in phase. We got a Nash criterion of about 0.91 for MIKE 11 and about 0.82 for HEC RAS. Generally, the different obtained results are satisfactory; the Nash criterion is very close to 1. We also note that the error in volume is of the order of 12%, but the peak flow has a very low error (less than 2%).

5.2. *Water level*

The water level changes, predicted by TELEMAC 2D, depends on several factors including flow rate, slope, roughness, etc... The model takes into account all these factors to calculate the different hydraulic parameters. The following (Figure 7) provides information on the variation of water levels in the Medjerdariver.

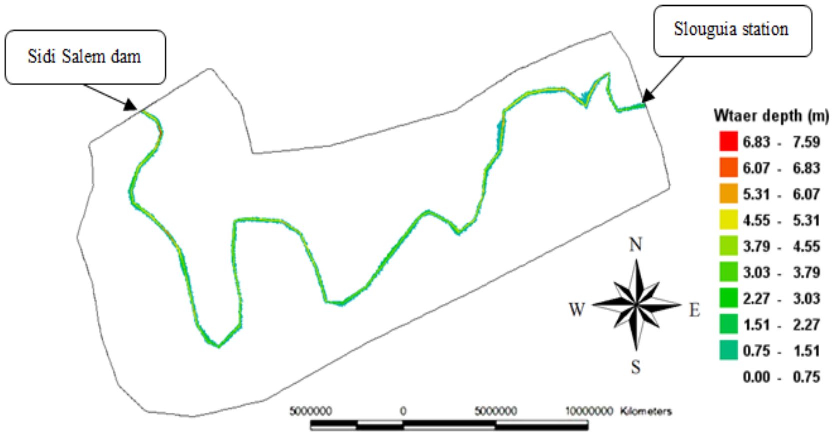


Figure 7: Evolution of the water level in the Medjerdariver, flood 2003.

During the floods of 2003, the maximum of measured water level at theSlouguia station is about 6 m. The Nash criterion is about 0.82, a value very close to 1, confirming again the reliability of our model.

5.3.*Velocity distribution*

The water velocity in river depends also on several conditions, in particular the flow, topography, roughness, obstacles, vegetation, etc...

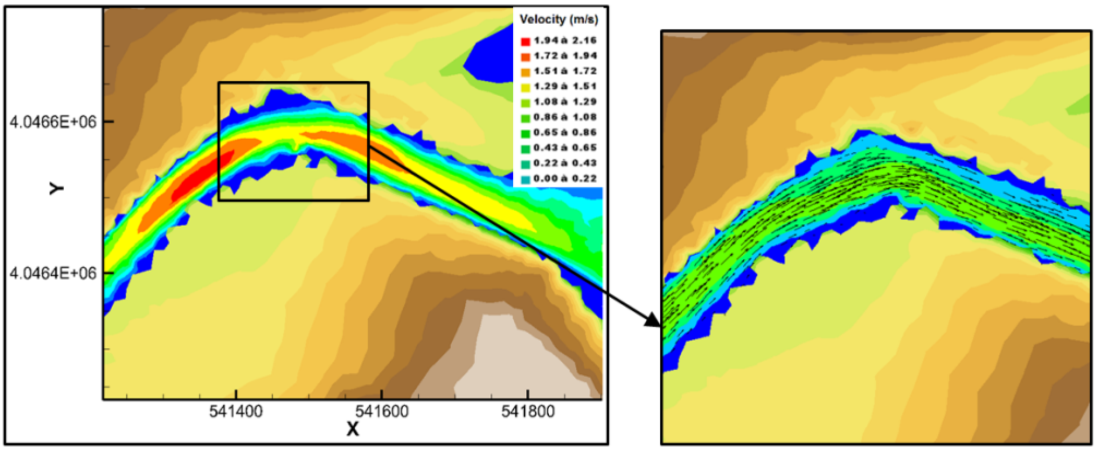


Figure 8: Evolution of the velocity fields (u, v) in the Medjerdariver, flood 2003.

Below, we present the velocity map that provides information about thevelocity field evolution in Medjerda in both directions (u, v) from Sidi Salem dam to the Slouguia Station. The velocity indicator is shown by arrows. The forecasting velocity by the 2D hydraulic model, TELEMAC 2D, shown by (Figure 9) varies on average between 0.35 m/s and 2.7 m/s.

5.4. *Evolution of the water surface*

Here, we were interested in the study of the behaviour of the Medjerda during the flood. For that, the model was run for a period of 5 days in order to show the water depth variation over time during the flood of 2003.

We note that over time the water level rises to a maximum level of about 6.83 m corresponding to a peak flow. The analysis shows that when the flow rate exceeds 350 m^3/s, the river overflows its banks. It is then found that the overflow phenomenon was accentuated in the downstreamdirection of the river, and that the water levels increased around the Slouguia station. Figure 10 showsseveral floodplain zones such as Tastour citylocalized about 10 km from the Sidi Salem dam.

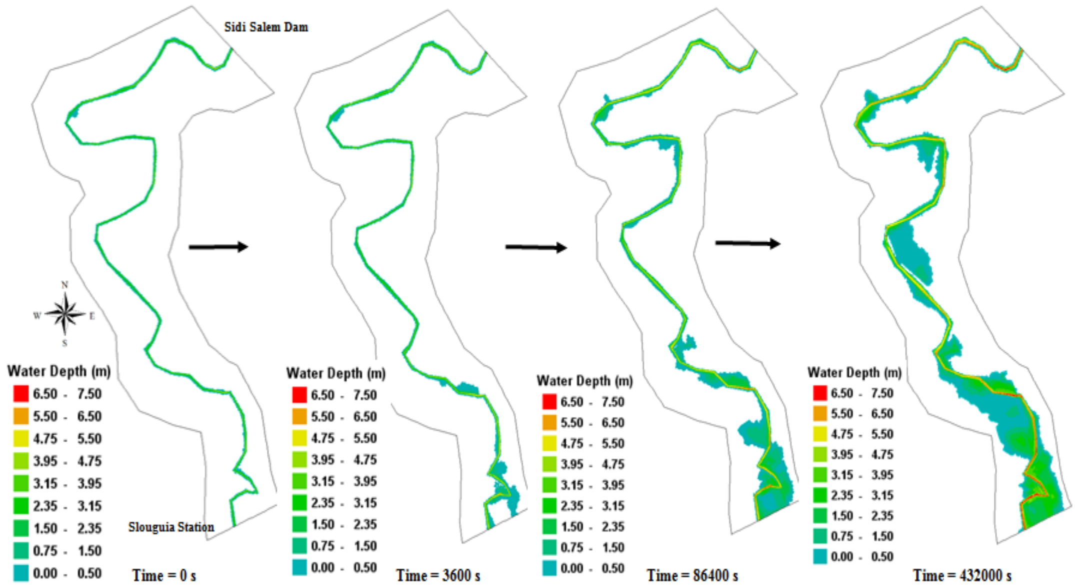


Figure 9: Evolution of the water levels in the Medjerda river, flood 2003.

5.5. Comparison between 1D and 2D models

This last part is dedicated to determine the advantages and limitations of tested models. Comparative studies were conducted to analysing the results of hydraulic simulations.In order to get meaningful comparisons, the simulationsshould be performed under the same flow conditions (same initial condition, same boundary conditions, same roughness...). The water level obtained by HEC RAS (1D), MIKE 11 (1D), and TELEMAC 2D are compared and the flow maps obtained by HECGeoRAS (1D) and TELEMAC 2D are compared too.

5.5.1. *Water surface profile*

A comparative study was carried out of the simulated water levels by TELEMAC 2D, by HEC RAS, and MIKE 11 (1D). The differences between the simulated water levels are generally low and the overall look of the water levels is the same. The mean difference between the measured water levels and those simulated is about 2 cm. We also note that at the outlet of the dam, the water levels calculated by the two models are superimposed, but at 10 km away from the dam, we find that 1D models overestimate the water depth comparing to TELEMAC 2D. There is a low difference (up to 5 cm) between the results of different simulations (Figure 11). These differences confirm the importance of the roughness parameter in the floodplains of the river.

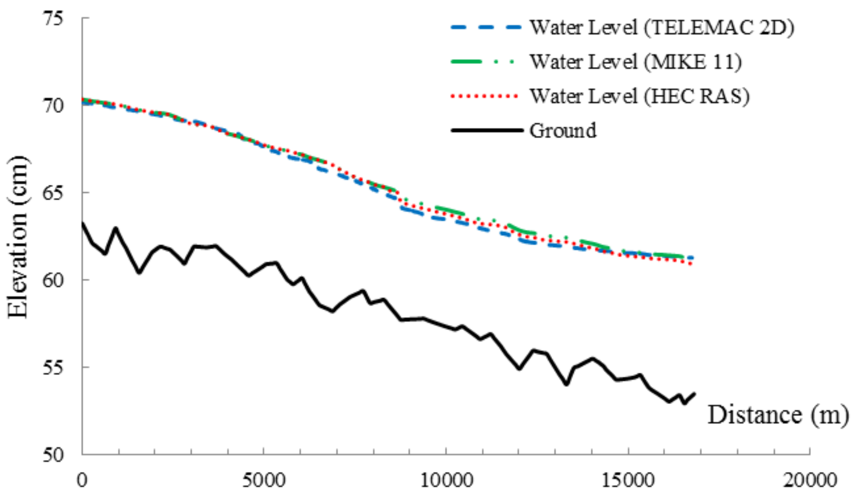
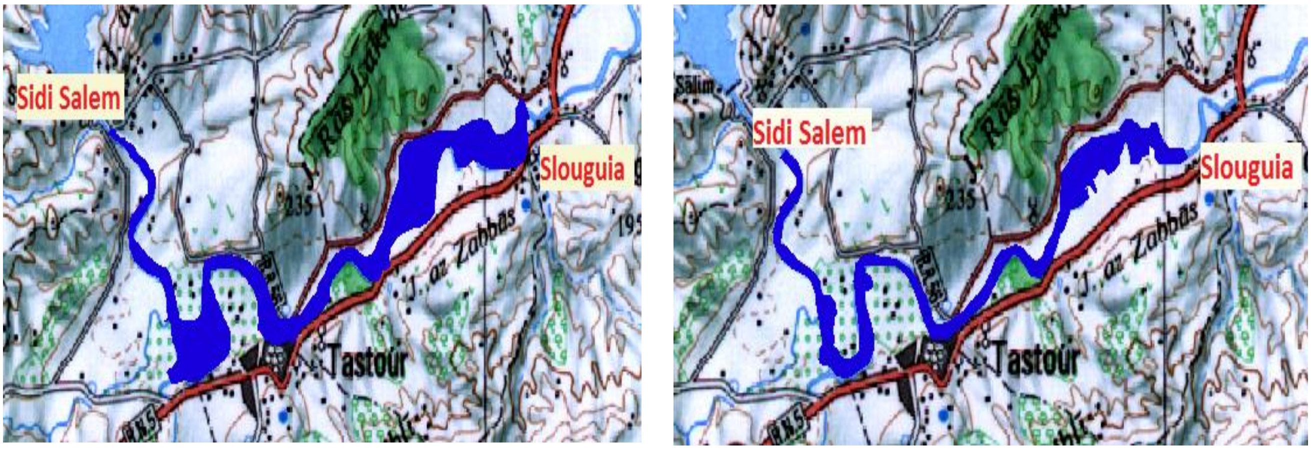


Figure 10: Comparison of water levels obtained by the different models at the Medjerda, flood 2003.

The disagreement can be explained by the factthat the geometry has not been inserting with the same manner. In 1D models, cross sections are interpolated so that the geometry is much smoother comparing to the 2D model. It is also important to note that TELEMAC 2D, MIKE 11, and HEC RAS do not use the same numerical scheme (finite difference method, finite element method, etc…). In the case of an overflow, this will generate calculation errors. This may explain the differences between water levels predicted by the different models shown in (Figure 11).
We calculate the Nash criterion in order to evaluate the reliability of the different tested models. We got a Nash criterion of about 0.89 for TELEMAC 2D, about 0.91 for MIKE 11 and about 0.82 for HEC RAS. Generally, the differences between the simulated results are satisfactory; the Nash criterion is very close to 1.

5.5.2. *Flood Map*
To better showthe difference between the two models used in this current research, we considered a comparative analysis of the two flood maps established by HEC GeoRAS and TELEMAC 2D. The analysis shows that there is a similarity in the determination of flood zones (Figure 12).



HEC GeoRAS (1D) TELEMAC 2D

Figure 11: Floodplain mapping of the Medjerda river during the flood 2003.

However, it appears clear that there is a difference in the estimate of the river overflow rate. The Figures 12 show that HEC RAS overestimates the extent of the flood zone compared to TELEMAC 2D. These few local differences may be explained by lack precision during modelling. In fact, a small overestimation of the water depth may cause a thin layer of water that contributes to the expansion of the flooded zone.

Conclusion

Flood forecasting deserves special attention, nowadays several methods have been developed for flood forecasting, especially numerical modelling. The present study has achieved modelling and simulations, leading to a first description of the flood extent and the behaviour of the water level profile of the Medjerdariver. The obtained results are encouraging. It is undeniable that 1D model are certainly easy and fast to build and to run, but the results of such models have significant inaccuracies in the floodplains. However, 2D models can correct this problem but it needs much more time for the flows implementation and simulations. 1D models such as HEC RAS and MIKE 11 are recommended for the modelling of long river; and they can also be used in the context of rapid studies that do not require too much precision especially in the floodplain level. Due to the heavy construction and simulation, 2D models will instead be used as part of studies to an important point in the delineation of flooded areas as well as in the definition of water levels in the flood plain.

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