GeoScience Engineering

SEDIMENT TRANSPORT MODELING AT THE OUED FODDA WATERSHED LEVEL USING HEC-RAS 1D SOFTWARE

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ABSTRACT

The objective of the current work is to determine the amount of sediments transported upstream and at the level of Oued Fodda dam. The latter is considered one of the first large dams built in Algeria. It's exposed to a serious siltation problem that reduces its capacity every year. The simulation was executed using the HEC-RAS software, for the period varied from January 01, 2016 to April 30, 2016. The modeled section consisted of about 9999 m length, subdivided into 141 river stations distant from each other by 70 m. The observation of the studied river section bed- profile was selected as a criterion for comparing the results of the model with the real values observed. A roughness coefficient of 0.031 was used. A quantitative estimate with a determination coefficient, R2, of 0.92 was used to support the validity. The mass and concentration of sediments increased significantly in the cross-sections located at the dam upstream. A total cumulative mass was estimated at approximately 712699 tons, just upstream of the dyke, and a maximum concentration of 22.35 g/l was observed, particularly for three main sections selected upstream of the Fodda wadi. However, at the reservoir level, the concentration variability is observed during flood periods, i.e., only for the most important flows.

Keywords: GIS; HEC-RAS; Oued Fodda dam; Sediment transport; Siltation.

1 INTRODUCTION

Due to its importance, the transport of solid materials is a major problem in the Maghreb countries [1]. In Algerian rivers, this problem has always arisen in an acute way. Due to the lack of data, its assessment remains complex. The enormous quantities of sediments transported are at the origin of the progressive reduction of the reservoirs storage capacity. In fact, around 65 million cubic meters of silt is deposited annually in Algerian dams [2]. The various bathymetric surveys effected during the period (1986–2008) by the National Agency for Dams and Transfers (ANBT) on all 59 dams in exploitation revealed that the volume lost through silting was 898 mm³, i.e. 13.4% of the total reservoirs volume [3–4].

Numerous methods for estimating solid transport exist in the literature, including models that explore physical laws such the St. Venant equation for the liquid phase, and the transport equations for the solid phase [5]. Although they faithfully represent transport phenomena, these models require the introduction of a large number of parameters. Mathematical models have been developed using three approaches: empirical models, which relate the flow of sediment to the outfall, the various climatic and biophysical explanatory variables [5]. Its major disadvantage is the difficulty of its calibration for large basins [6]. Regressive models (flow-TSS) deduced from the ratio, between the observed flow, the values of the suspended solids concentration (Lefkir, 2009), and the conceptual models, which consider erosion dynamics. These models have the advantage of estimating flows for different time steps, but they require a relatively long calibration period, and peaks in TSS concentration which are generally underestimated [7].

Researches has intensified and expanded to establish new methods: 1D models, numerous 2D models and finally 3D models, which have been developed to simulate sediment transport processes [8]. In view of this, our work is

DOI 10.35180/gse-2023-0097

a part of a one-dimensional solid material transport modeling using the HEC-RAS software. This code was created by the U.S. Army Corps of Engineers and has been employed by several engineering firms and governmental organizations [9]. It calculates the sediment transport capacity associated with each cross-section as a control volume for all grain sizes [10]. The Wadi Fodda sub-watershed was selected for this study. This basin is exposed to a major problem of soil degradation, which accelerates the silting phenomenon at the level of the Wadi Fodda dam. The latter is considered one of the first large dams built in Algeria. It's intended for the irrigation of the Middle Cheliff perimeter [11]. Its storage capacity has decreased considerably over the last 18 years. The siltation rate has been estimated at about 54.29% and the bathymetric condition of the reservoir has become very worrying [12].

2 STUDY AREA

The Upper and Middle Cheliff watershed is located in the west of the Fodda Wadi basin, which is covering a surface area of 1153.5 km^2. The larger Cheliff watershed, which is in the northwestern Algeria, is mostly occupied by the latter and located in its northeastern portion (Fig. 1).

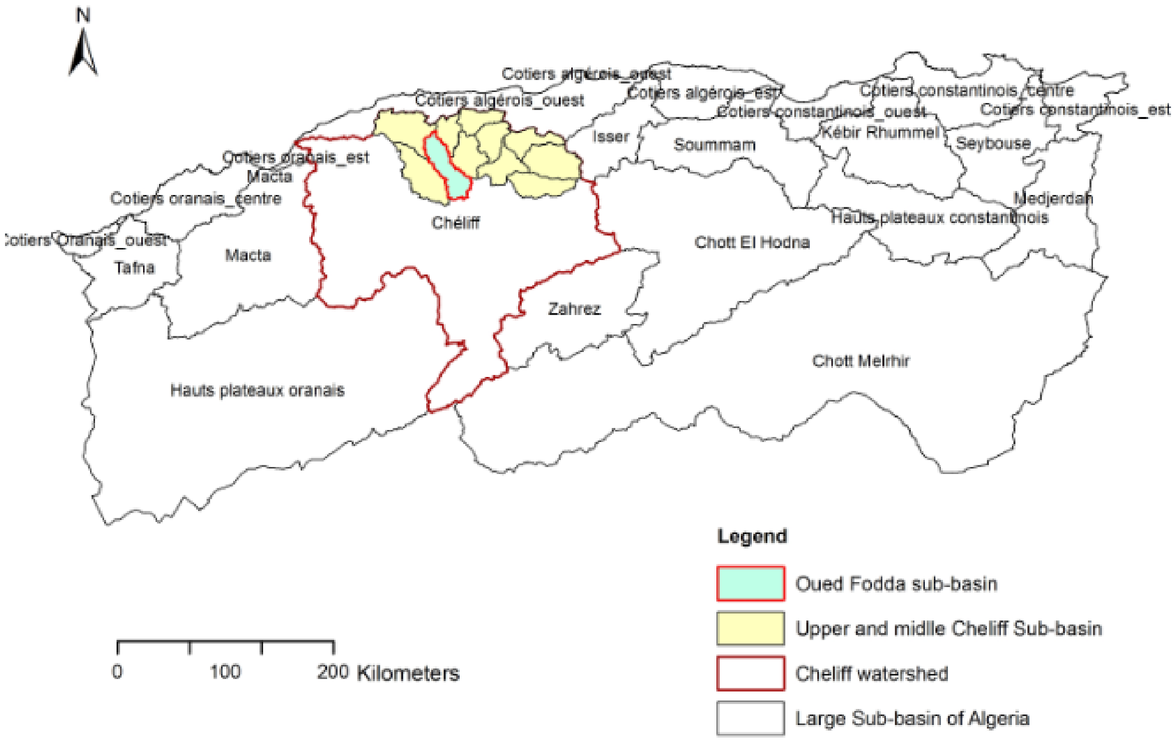

Figure 1. *Oued Fodda watershed*

The Oued Fodda sub-basin has a considerable relief, an elongated shape (Fig. 2), and a highest point can reach 1950,7 m [13]. With 282 temporary wadis and 81 permanent wadis totaling roughly 1053.45 km and 897.16 km, respectively, it features a complex hydrographic network. It is mostly drained over a 92.14 km length by the Oued Rouina [11]. Our study area is exposed to a serious problem of soil degradation. Gully erosion has been identified towards the upstream of the basin [14] (Fig. 3). This is at the origin of an important production of sediment, which accelerates the silting process at the level of the Wadi Fodda dam reservoir (Figs. 4 and 5). It collects an annual volume of silt of 3.2 million m^3 [15]. An annual loss of its storage capacity has been estimated to be about 4,248 km^3, i.e. a silting rate of 45.43% in 2015 [13].

Vol. 69 (2023), No. 2
pp. 160–178, ISSN 1802-5420
DOI 10.35180/gse-2023-0097

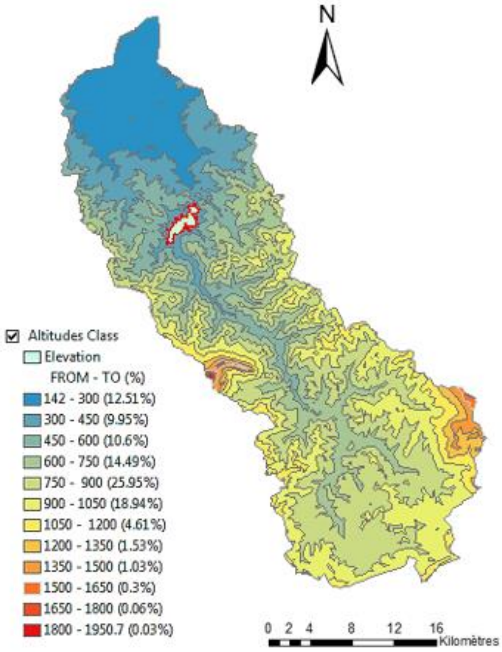

Figure 2. *Hypsometric Oued Fodda watershed map*

Figure 3. *Gully formation at the Oued Fodda watershed*

Figure 4. *Oued Fodda dam reservoir view with an initial capacity of 228 Mm^3 (Photo: Remini, 2008)*

Figure 5. *Vase deposit upstream of the Oued Fodda dam (Photo: Benkaci, August 2017)*

The physiographic characteristics of the Oued Fodda sub-watershed were calculated based on ArcGis™ software [16] and summarized in Table 1 below:

Table 1. *Physiographic characteristics of the Oued Fodda sub-basin*

Characteristics	**Value**	**Observation**
Area (km^2)	1153.5	-
Compactness index K_c	1.74	the basin is elongated favoring slow flow of runoff
Max. Altitude (m)	1950.7	Highest point of the basin
Average Altitude (m)	709.40	-
Median Altitude (m)	750	Represents 50% of the total surface area of the basin
Minimal Altitude (m)	142	Watershed outfall
Equivalent rectangle length (km)	93.144	-
Equivalent rectangle width (km)	12.384	-
Mean slope index Imoy (%)	1.72	-
Global slope Index Ig	0.1	Strong relief
Drainage density D_s (m)	328.16	-

3 MATERIALS AND METHODS

At the Wadi Fodda dam reservoir, the HEC-RAS program was primarily used to model the transport of sediment. It enables for all grain sizes and a control volume calculation of the transport capacity associated with each cross-section (Fig.6). The Exner equation, also known as the mass conservation and the sediment continuity equation, provides the foundation for its basic idea [10]:

$$(1-\lambda_p)B\,\frac{\partial \eta}{\partial t} = -\frac{\partial Q_s}{\partial x} \qquad (1)$$

where:

- λ_p porosity of active layer,
- B channel width [m],
- η channel elevation [m],
- Q_s sediment load transported [m^3/s],
- X distance [m],
- T time [s].

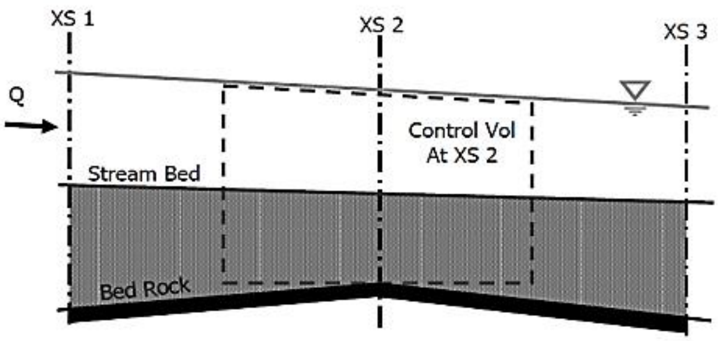

Figure 6. *Control volume used in HEC-RAS sediment calculations [17]*

Vol. 69 (2023), No. 2
pp. 160–178, ISSN 1802-5420
DOI 10.35180/gse-2023-0097

3.1 Model input parameters

The calculation of sediment transport upstream and at the Fodda Wadi Dam requires three input data files, as shown in Fig. 7.

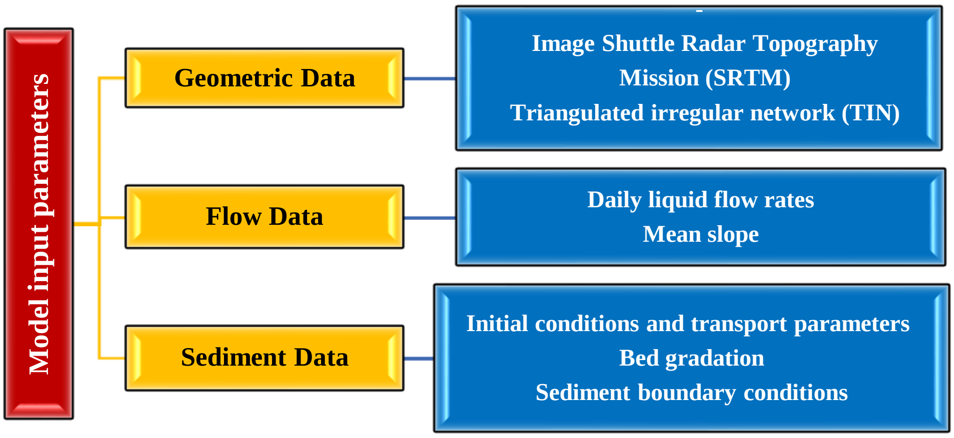

Figure 7. *Methodological diagram of the input parameters in the HEC-RAS model*

The Manning's coefficient is the most important parameter to be adjusted in the calibration of the HEC-RAS model. The use of a single Manning's coefficient may not be sufficient and adequate to represent the true roughness of a river under different flow conditions [18]. Due to assumptions in the data or the model limitations, no model will give findings that are exactly in line with the real results. But it is necessary to achieve a reasonable correlation between observed values and model outcomes [10].

For our model, the adjustment of the Manning coefficient is performed following the hydraulic simulation of the unstable flow over a period from January 01, 2016 until April 30, 2016. The water surface elevations (WSEl) associated with the measured flow rates and the output flow rates estimated by the HEC RAS software are compared as part of the calibration procedure. The values of the observed (measured) liquid flows are based on the daily liquid flows obtained at the level of the Oued Fodda dam direction during the considered period. Several roughness values were tested: 0.030, 0.031, 0.032, 0.033, 0.034 and 0.035. The Manning value retained (for which the error is minimal) is equal to 0.031 [13].

3.1.1 Geometric Data

The geometry of the studied section was initially created in ArcGisTM using a form of digital geographic vector data "TIN" (Fig. 8) extracted from the SRTM Worldwide Elevation Data (3 arc second Resolution 90 m) of the Oued Fodda watershed (Fig. 9). These data are then exported using the HEC-GeoRas software and visualized through the "Geometric Data" window (Fig. 10) with the HEC-RAS software [13]. The modeled section was approximately 9999 m in length ،subdivided into 141 river stations of approximately 70 m per part. Section 69 is located downstream (immediately upstream of the Wadi Fodda dam) at a distance of about 50 m (Fig. 11). On the other hand, section 9945 is located upstream. It is therefore, considered as the first section of the upstream Oued Fodda.

Vol. 69 (2023), No. 2
pp. 160–178, ISSN 1802-5420
DOI 10.35180/gse-2023-0097

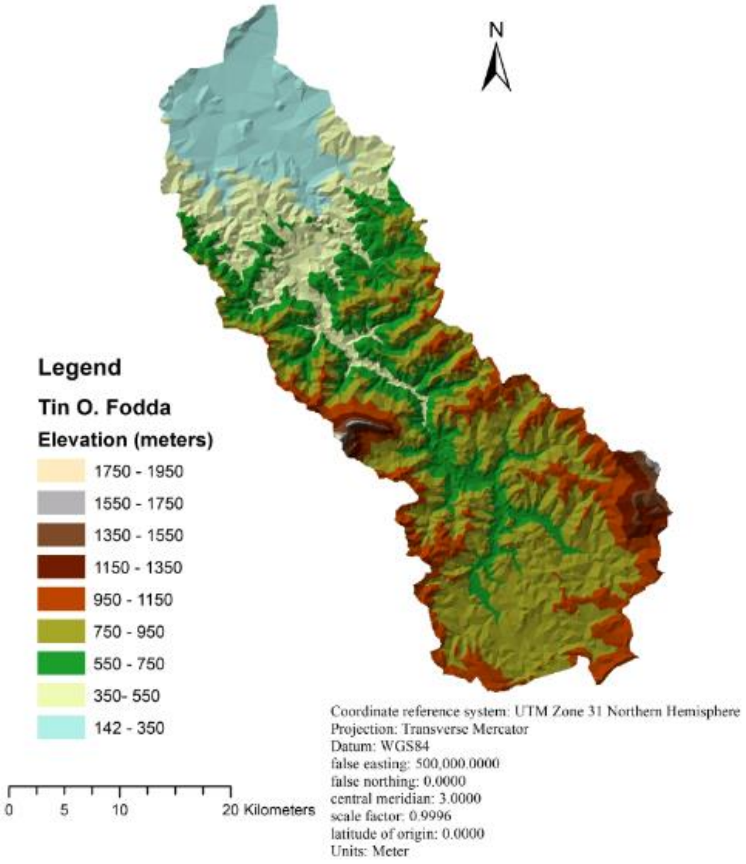

Figure 8. *Triangulated irregular network (Tin) of the Oued Fodda watershed*

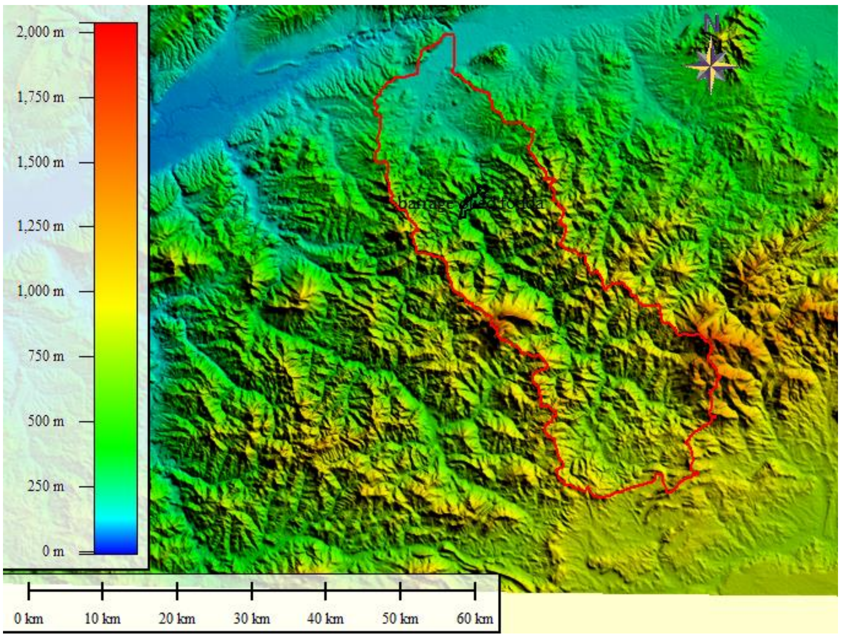

Figure 9. *Shuttle Radar Topography Mission image, SRTM Worldwide Elevation Data (3 arc second Resolution) of the Oued Fodda watershed*

Vol. 69 (2023), No. 2
pp. 160–178, ISSN 1802-5420
DOI 10.35180/gse-2023-0097

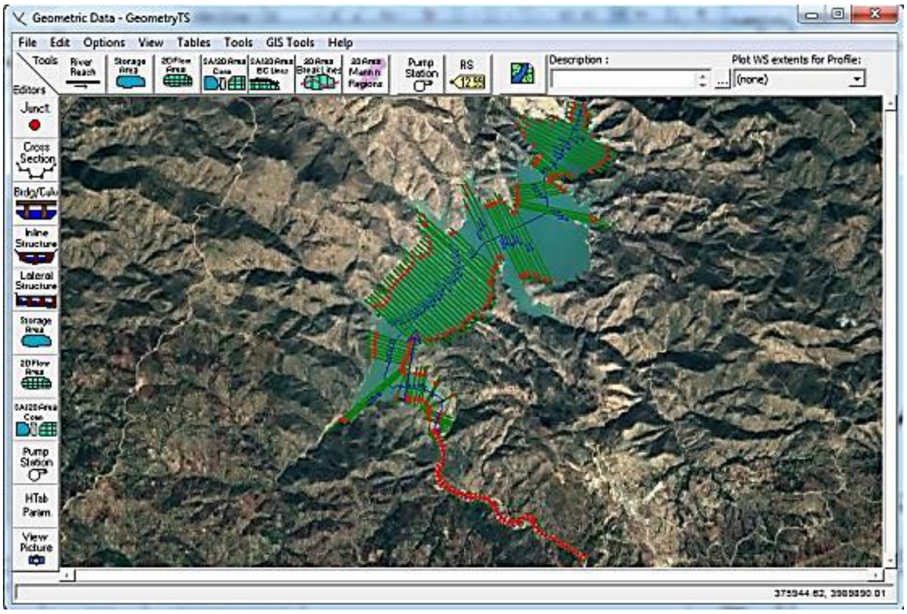

Figure 10. *Geometrical data window visualized through a Google Earth image*

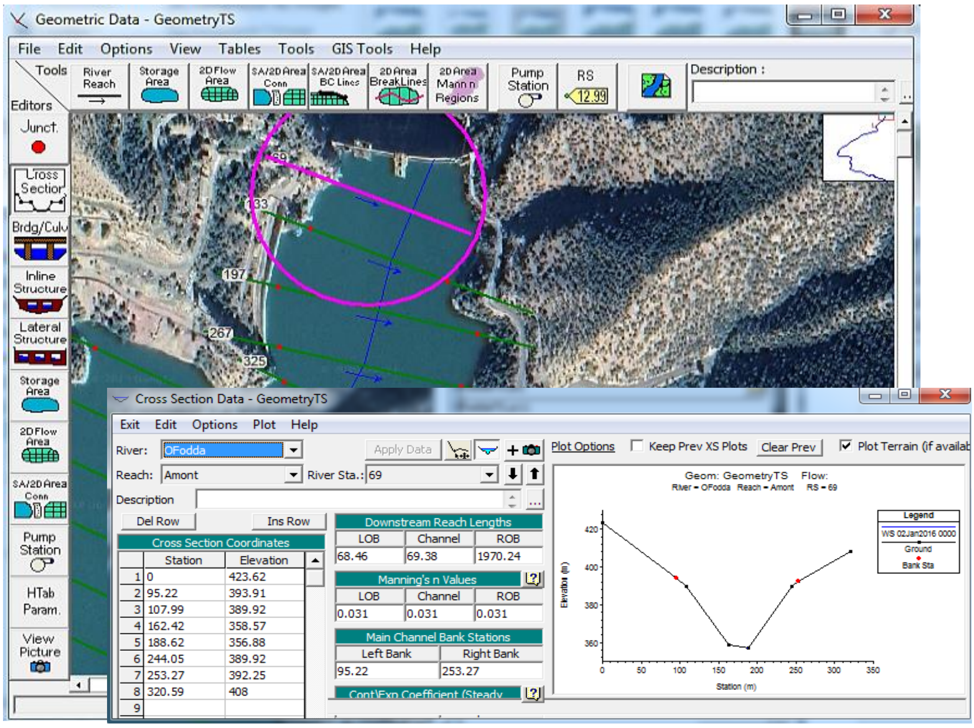

Figure 11. *Characteristics of the upstream cross-section (69) of the Oued Fodda Dam dike*

Vol. 69 (2023), No. 2
pp. 160–178, ISSN 1802-5420
DOI 10.35180/gse-2023-0097

3.1.2 Flow data and boundary condition

The simulation of sediment transport begins with the creation of a quasi-unstable flow file. Two boundary conditions are considered (Fig. 12).

- The first is selected at the first cross section of the Fodda wadi (section 9945). For this condition, the data of the daily liquid flows observed at the dam upstream have been introduced with a time step of 12 days considering the duration of the simulation, which runs from January 1, 2016 to April 30, 2016.
- The second boundary condition is located at the downstream (wadi Fodda dam dike). It simply corresponds to the value of the average slope (0.0242) at the level of the cross-section considered (section 69).

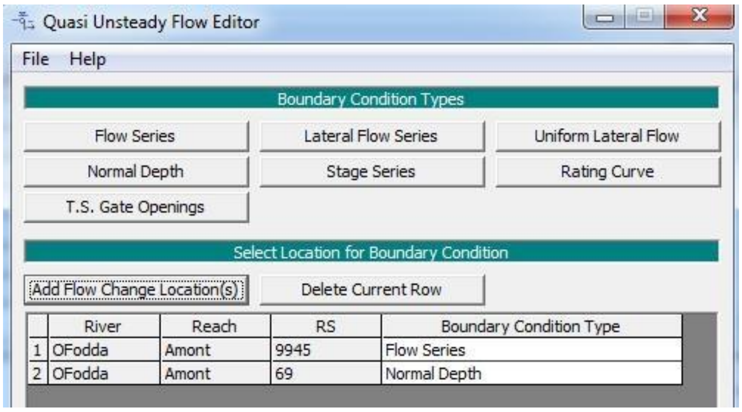

Figure 12. *HEC-RAS window of the quasi-unstable flow boundary conditions*

The obtained flow hydrograph (Fig. 13) illustrates the occurrence of two major floods in March 2016. The first is observed on March 12, corresponding to a flow rate of about 27 m^3/s, and the second is observed on March 20 with an estimated flow rate of 20.66 m^3/s.

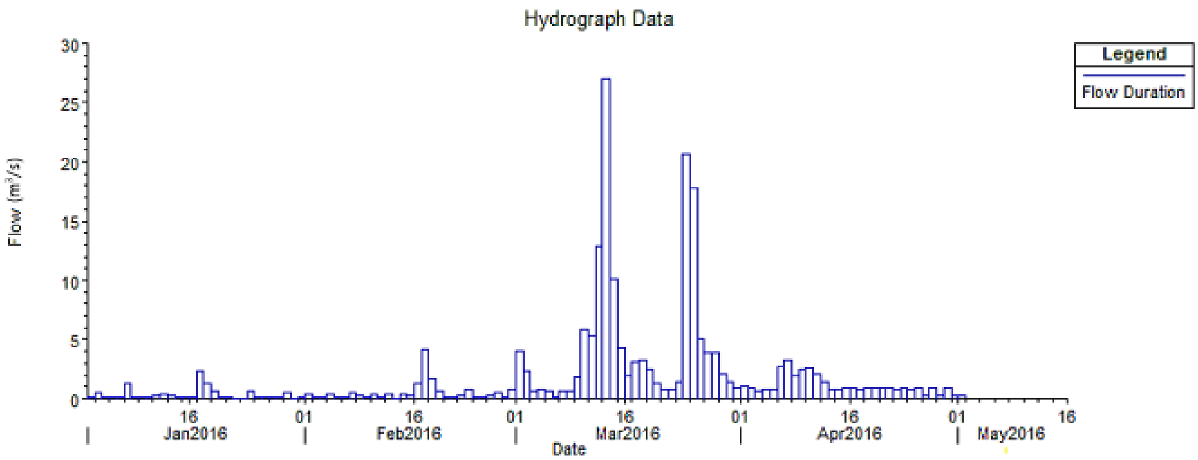

Figure 13. *Flow hydrograph*

Vol. 69 (2023), No. 2
pp. 160–178, ISSN 1802-5420
DOI 10.35180/gse-2023-0097

3.1.3 Sediments data

The sediment data file is based on three main input quantities. These are illustrated in Fig. 14.

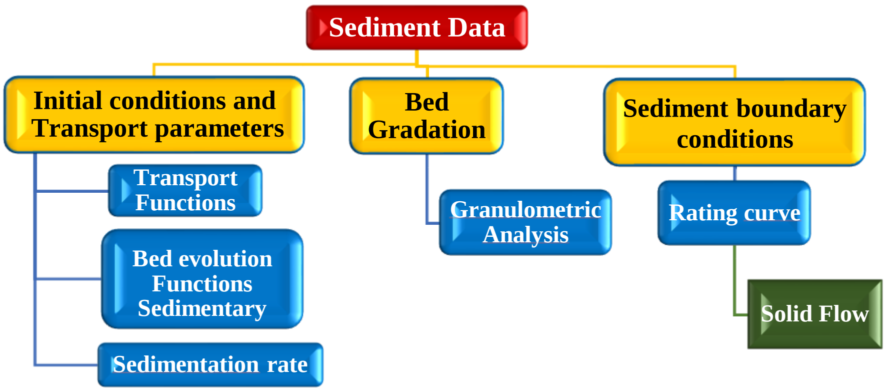

Figure 14. *Methodological diagram of the sediment data file*

3.1.3.1 Bed gradation

The "bed gradation" data file is based on the results of the Granulometric analysis (Table 2). Samples were collected from several segments along Wadi Fodda, just at the dam upstream. The granulometric analysis sample was effected at the National Laboratory of Habitat and Construction (LNHC) of Oued Samar (Algiers). The curve is represented in Fig. 15.

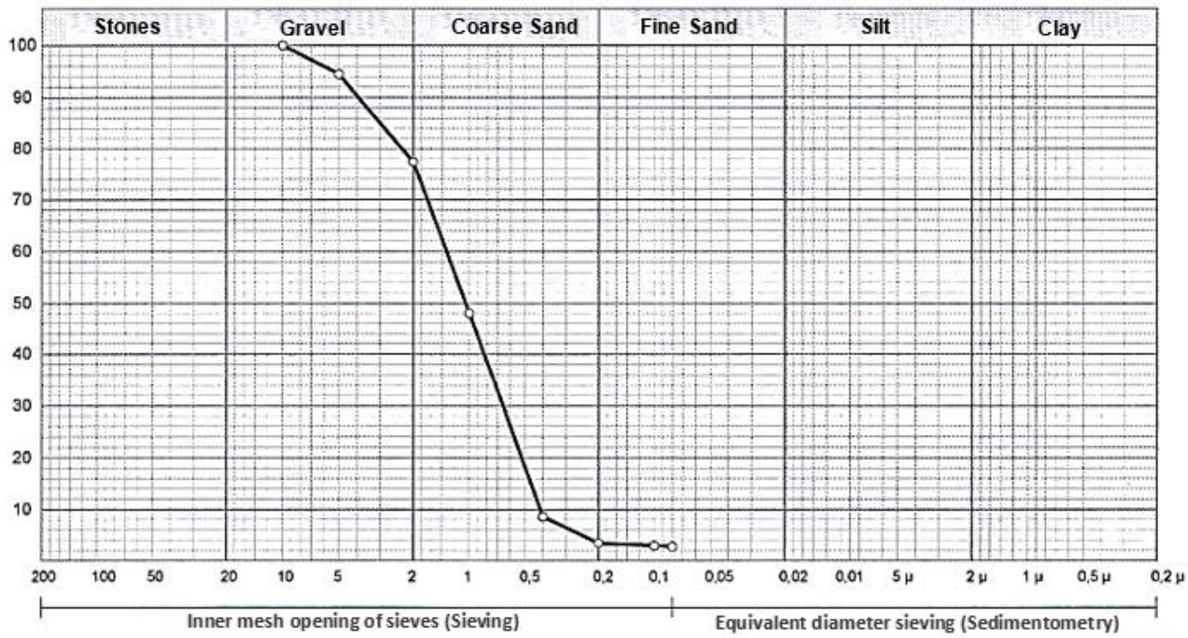

Figure 15. *Grading curve of the sample taken along the upstream section of the Oued Fodda dam*

Vol. 69 (2023), No. 2
pp. 160–178, ISSN 1802-5420
DOI 10.35180/gse-2023-0097

Table 2. *Granulometric analysis results*

Upstream Oued Fodda Sample			
Grains (mm)	Coarse sand	Gravel	Fine sand
Percentages (%)	73.98 %	22.63 %	3.39 %

By default, HEC-RAS uses 20-grain classes. The fraction of each class is specified as a percentage, or converted to millimeters. (Fig. 16) illustrates the gradation curve at the upstream bed section of the Oued Fodda dam.

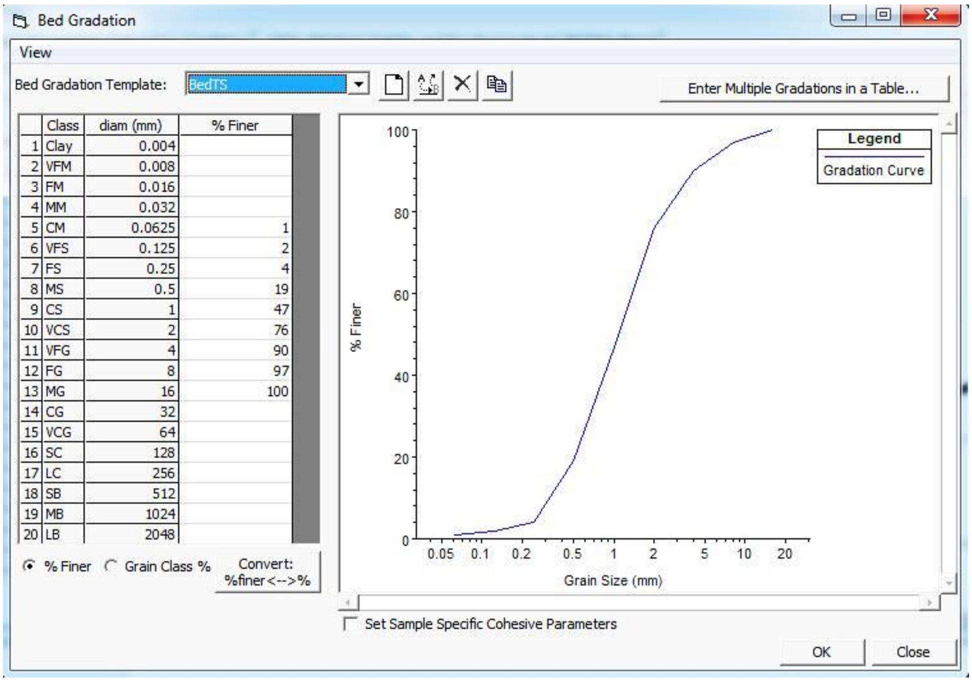

Figure 16. *Bed gradation of the upstream Oued Fodda section*

3.1.3.2 Initial conditions and transport parameters

Several combinations have been affected based on the eight transport functions, the five sedimentation rate equations and the two sedimentary bed evolution models "Active layer and Exner 5". The input parameters are defined and justified as follows:

- *Transport Functions*

Engelund Hansen's empirical formula for calculating the total load of sandy rivers, for a limited diameter range of 0.15mm < d < 5mm, is the suitable function for the evaluation of sediment transport upstream of the Wadi Fodda Dam. It is given in the following dimensionless form [19]:

$$\frac{\overline{q_S}}{\sqrt{\left(\frac{\gamma s}{(\gamma w-1)}\right) g.d^3}} = 0.08\left(\frac{K^2.y^{\frac{1}{3}}}{g}\right)\tau^{*\frac{5}{2}} \qquad (2)$$

where:

K overall Stickler's coefficient including the roughness of the banks and the grains that constitute the background,

Y flow height.

This choice is validated based on the results of the granulometric analysis of our sample (Fig. 13).

It shows that the upstream bed section of oued Fodda consist about 77.37% of sand with a grain size of between 0.177–0.707 mm in diameter and about 22.63% by gravel with a size ranging from 2 mm to 16 mm. So more than 90% of our sample are within Enguland Hansen’s granulometric validity range.

- *Sedimentary bed evolution functions*

The HEC RAS software proposes two functions: the Exner model: which considers an active three- bed layer and the "Active Layer" model, which is an approximate simplification of two active bed layers. Both models are based on the principle that the bed level increases proportional to the amount of mobilized particles (Fig. 17).

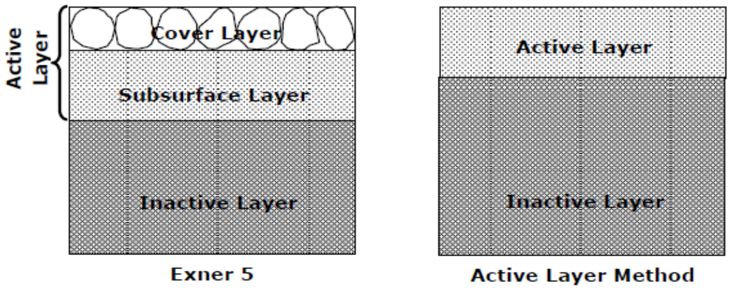

Figure 17. *Sedimentary bed evolution Models [20]*

The simulation did not work for the Active Layer model. However, Thomas' method (Exner 5) has been validated for all transport functions.

- *Sedimentation rate*

Of the five methods generated by the HEC-RAS software, the Van Rijn method was selected. It is based on three formulas expressed as a function of grain size:

$$\omega = \frac{(s-1)g.d}{18.\nu}; \qquad Si\ \ 0.001 < d \leq 0.1\ mm \qquad \textbf{(3)}$$

$$\omega = \frac{10.\nu}{d}\left[\left(\frac{1+0.01\ (s-1)^{0.5}}{\nu^2}\right) - 1\right] \qquad Si\ 0.1 < d < 1\ mm \qquad \textbf{(4)}$$

$$\omega = 1.1[(s-1)g.d]^{0.5} \qquad Si\ d \geq 1\ mm \qquad \textbf{(5)}$$

where:

ω particle velocity (m/s),
ν kinematic viscosity (kg/m.s),
s specific gravity of the particles,
d particle diameter (m).

The Van Rijn used a form factor of 0.7 to calculate the sedimentation rate of the particles, which is also the same factor for the natural sand. Therefore, this method was used for our model (21–10).

3.1.3.3 Sediment boundary conditions

A “rating curve“ serves as the boundary condition for the upstream river station (9945). This determines a sediment load based on the water flow. It represents the sediment load, from the upstream station, during the simulation. Therefore, the model uses this condition and calculates the change in bed shape, based on the sediment properties, the selected transport function, and other hydraulic parameters. In our study, the evaluation of sediment transported to the Oued Fodda dam, depends mainly on the solid flow series input data. The available observation file was provided from the Pontéba défluent hydrometric station obtained at the level of the national water resources agency (ANRH). It is a series of solid transport data over a 29-year hydrological period (1983–2011). This station is located on the downstream section of the Wadi Fodda dam. However, no hydrometric station is available at the upstream section (Fig. 18) [13].

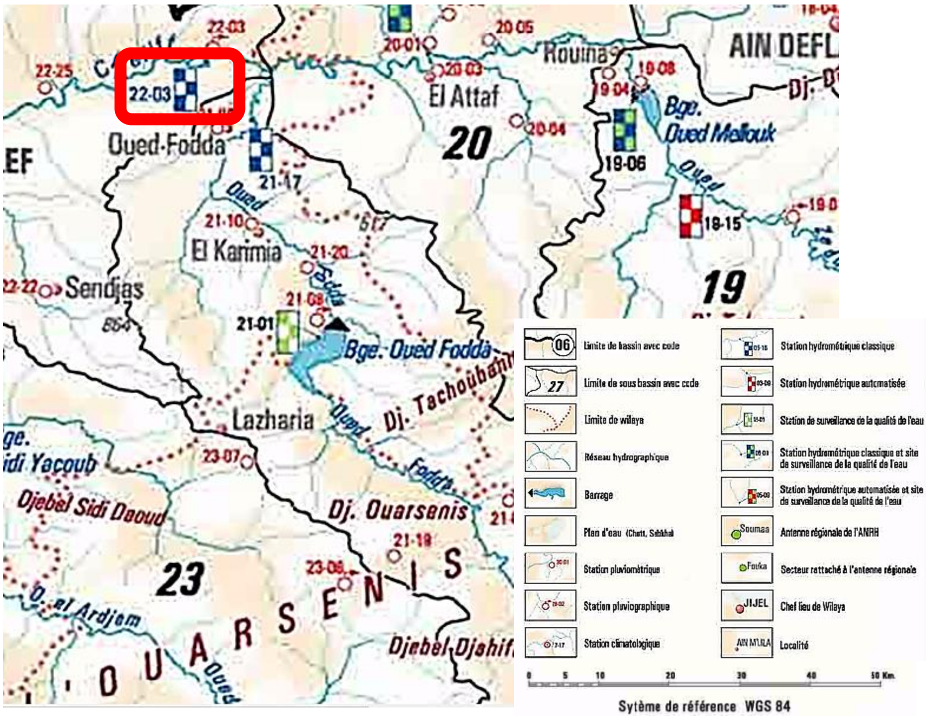

Figure 18. *Situation of the Pontéba- défluent hydrometric station*

To determine the sediment transport data at the upstream sections dam, we proceed as follows:

- we performed a liquid-solid flow correlation based on data from the Pontéba-Défluent downstream station. The founded results are illustrated in Fig.19.
- we used the established relation for the calculation of the upstream solid flows, based on the daily liquid flows file obtained within the Fodda Wadi Dam Directorate. The relationship was found to have the following form:

$$Q_s = 4.0995\ Q_l^{1.2546} \qquad (6)$$

The sediment calibration curve, chosen as a boundary condition, was produced by taking into account the data computed using equation 6 above. The resulting curve (Fig. 20) shows the proportional increase in sediment load as a function of liquid flow [13].

Vol. 69 (2023), No. 2
pp. 160–178, ISSN 1802-5420
DOI 10.35180/gse-2023-0097

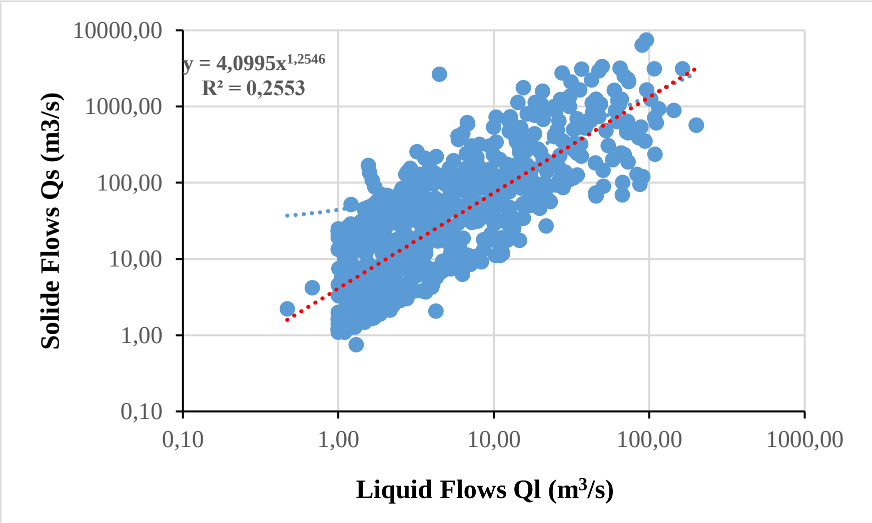

Figure 19. *Liquid-Solid Flow Correlation*

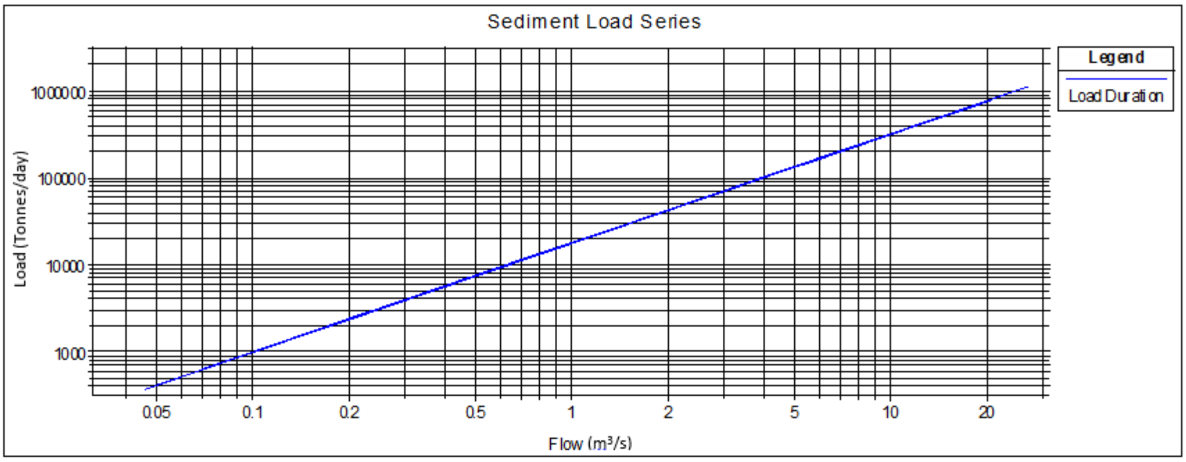

Figure 20. *Sediment specific load curve*

3.2 Model calibration and validation

The simulation was executed for the period from January 01, 2016 to April 30, 2016. An output file of all the hydraulic parameters is obtained for the full simulation period. For sediment transport, the results are also displayed in a "Sediment Output" file. These were quite vulnerable to the new bed gradation. In order to compare the model findings with the actual observed values, bed profile observation (change in minimum elevation) was used as the comparison criterion. (Fig.21). The validation was selected particularly for the flood of March 12, 2016 with a liquid flow rate of 27 m3/s.

A lack of real data, since the solid flows used were obtained following the results of a correlation, which is due to the fact that there is no hydrometric station at the upstream. Moreover, the calibration of the modelled and observed profiles, showed the existence of an overestimation upstream (at the beginning of the simulation) and an underestimation downstream (near the dike). A quantitative estimate with a determination coefficient R^2 of 0.92, supported the model validation. This suggests a respectable level of agreement between model predictions and actual data.

Vol. 69 (2023), No. 2
pp. 160–178, ISSN 1802-5420
DOI 10.35180/gse-2023-0097

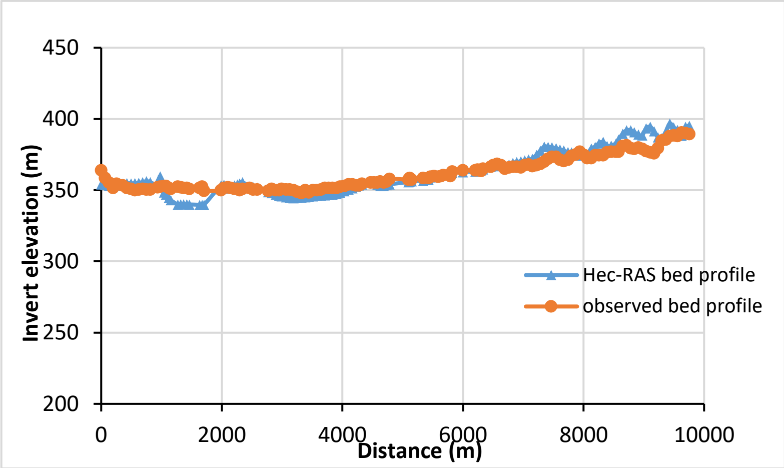

Figure 21. *Comparison of the observed and modelled bed profile by HEC-RAS*

4 RESULTS

Several parameters are displayed following the final sediment transport simulation, at the upstream and at the level of wadi Fodda dam. The main ones are:

4.1 Sediment mass cumulative variability

The cumulative mass of the studied, sediment bed section (in tons), can be calculated in time and space for each of the cross-sections. A gradual increase was observed throughout the simulation time (Fig. 22). The maximum sediment mass (accumulated) is that formed by very coarse sand (VCS). It reaches a value of approximately 653581.375 tons. However, very fine sand (VFS) is the material with the lowest mass. It is estimated at 22537,283 tons.

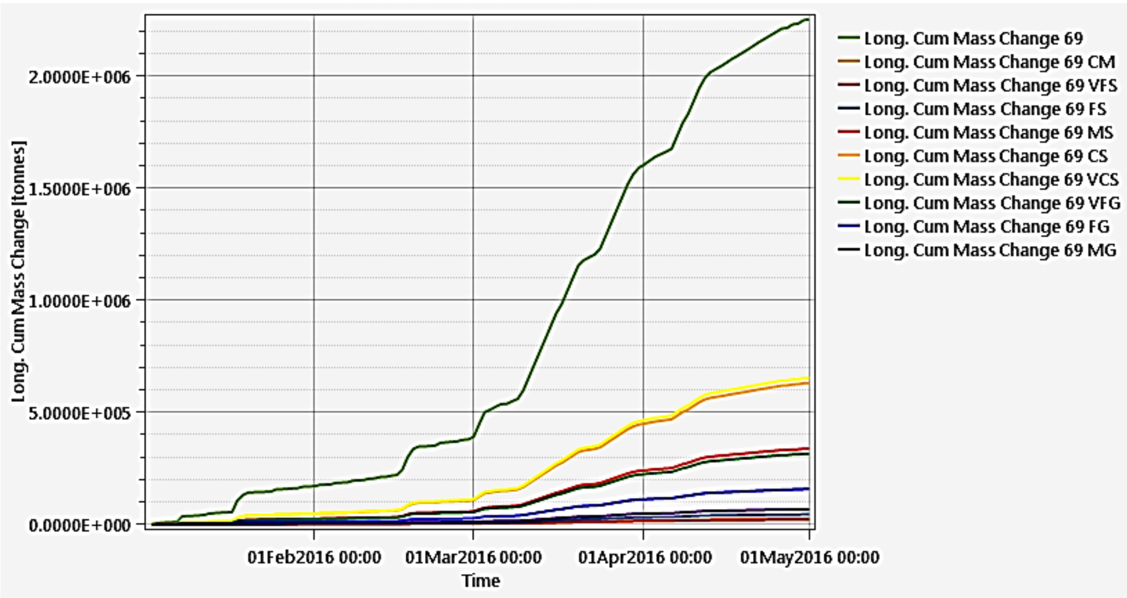

Figure 22. *Sediment mass accumulation as a function of time at section 69 (downstream)*

Vol. 69 (2023), No. 2
pp. 160–178, ISSN 1802-5420
DOI 10.35180/gse-2023-0097

The spatial accumulated mass sediment profile can also be plotted for each day of the simulation period. As an example of that, the March 12, 2016 flood, as shown in Fig. 23.

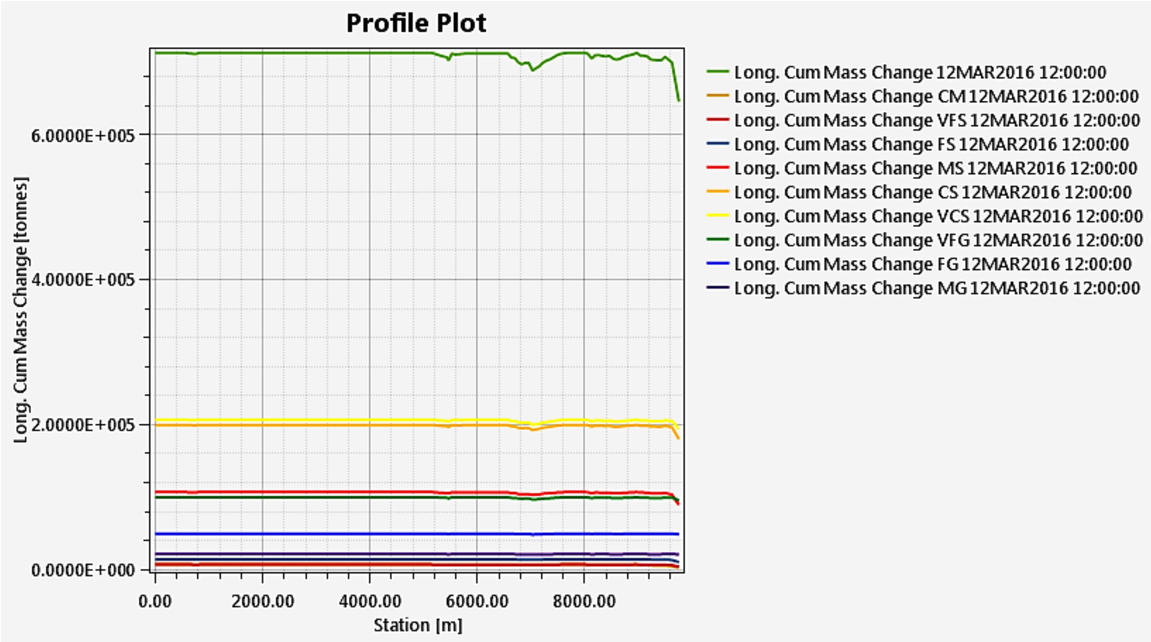

Figure 23. *Spatial sediment accumulation profile for the March 12, 2016 flood*

An increase in the (cumulative) sedimentary mass is observed from upstream (station 9945) to the downstream (5000–6500 m) from which the mass gradually stabilizes to reach a value of 712699.25 tons immediately upstream of the dike. Low flows or low velocities are responsible for the Fodda Wadi Dam reservoir's low fluctuation.

4.2 Sediments concentration variability

The total sediment concentration (in mg/litre) gradually increases in space and time. This variation can be affected by several parameters including flow rate, slope and bed roughness. A significant increase is observed particularly in the upstream cross-sections of the Fodda wadi dam. As an example of the sections: 9883, 8971 and 6824 are illustrated in Fig. 24. The maximum value reached for the three sections is estimated around 22.35 g/l. However, within the dam reservoir, the variation in concentration is only observed during high-water periods (month of March), i.e., only for the most important flows (stations 4861, 2896, 1182, 133 in Fig. 25).

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Vol. 69 (2023), No. 2
pp. 160–178, ISSN 1802-5420
DOI 10.35180/gse-2023-0097

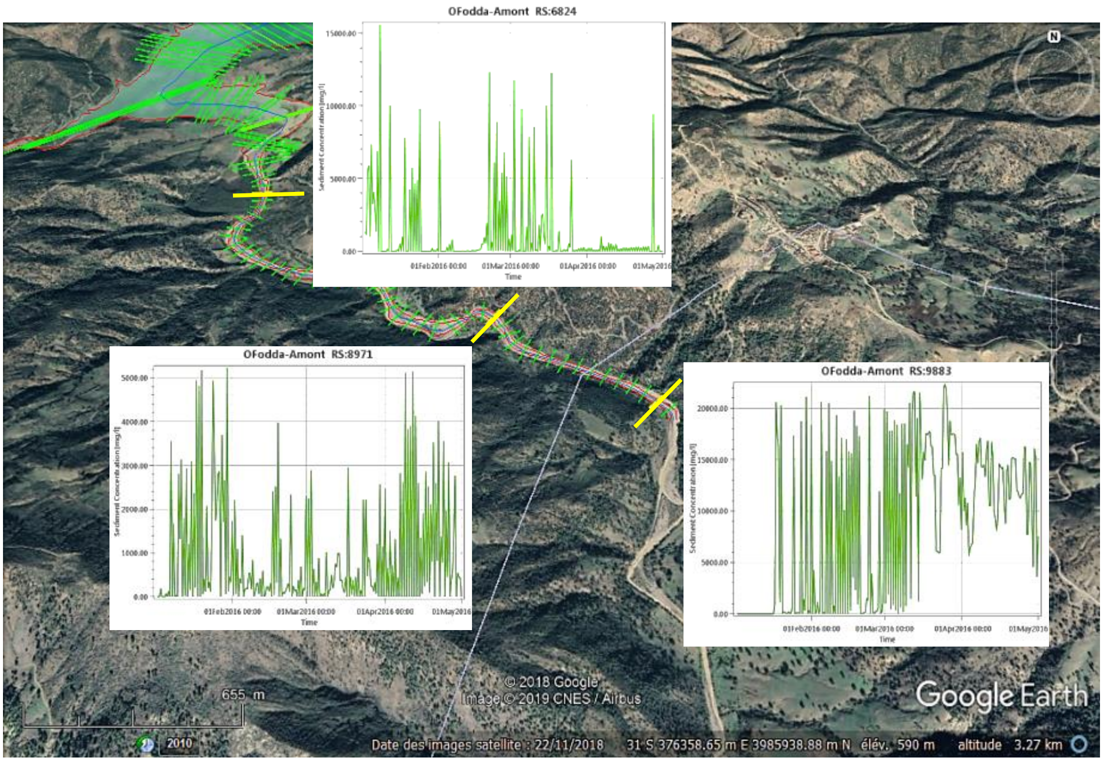

Figure 24. *Temporal concentration variability at the upstream sections of the Fodda Wadi Dam*

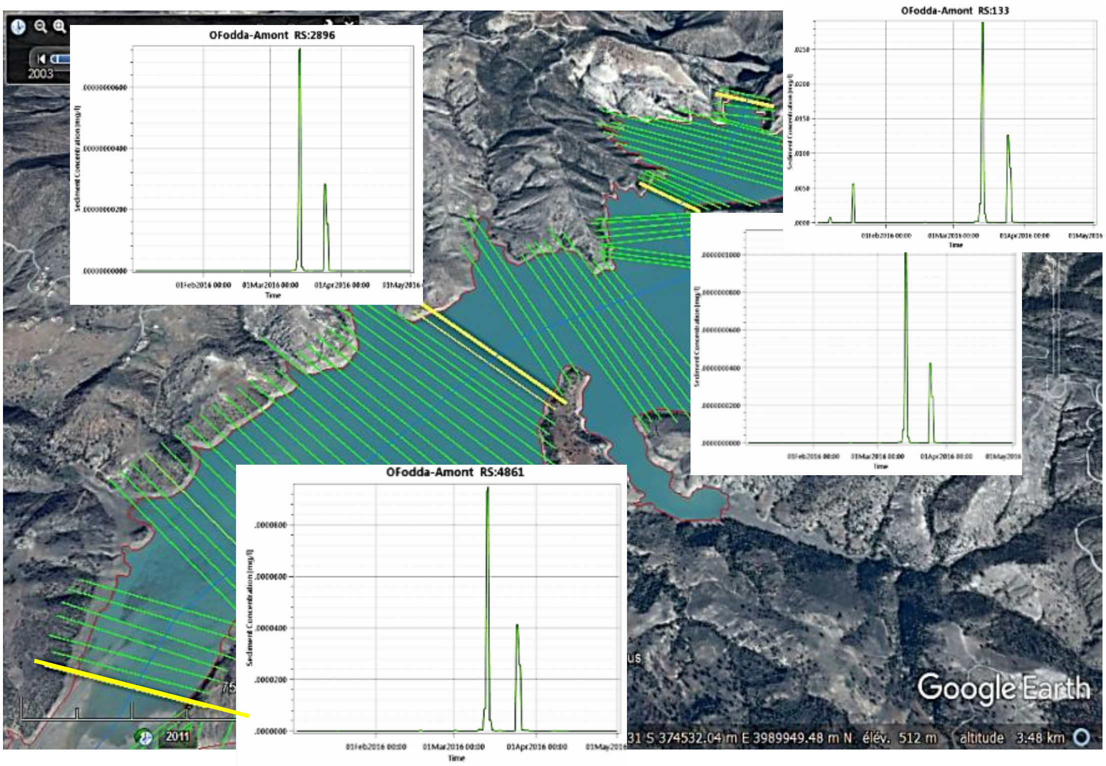

Figure 25. *Temporal concentration variability at the Wadi Fodda Dam*

Vol. 69 (2023), No. 2
pp. 160–178, ISSN 1802-5420
DOI 10.35180/gse-2023-0097

The spatial variation profile of the sediment concentration can be displayed for duration of simulation. A very significant variation is observed at the upstream cross-sections of the Fodda wadi and also at the sections from the downstream. An example is illustrated (Fig. 26) considering the two floods: 23 January and 2 February 2016. The maximum value of the sediment concentration was estimated around 6736.267 mg/l for the January 23rd flood and 12278.532 mg/l for the February 2nd flood.

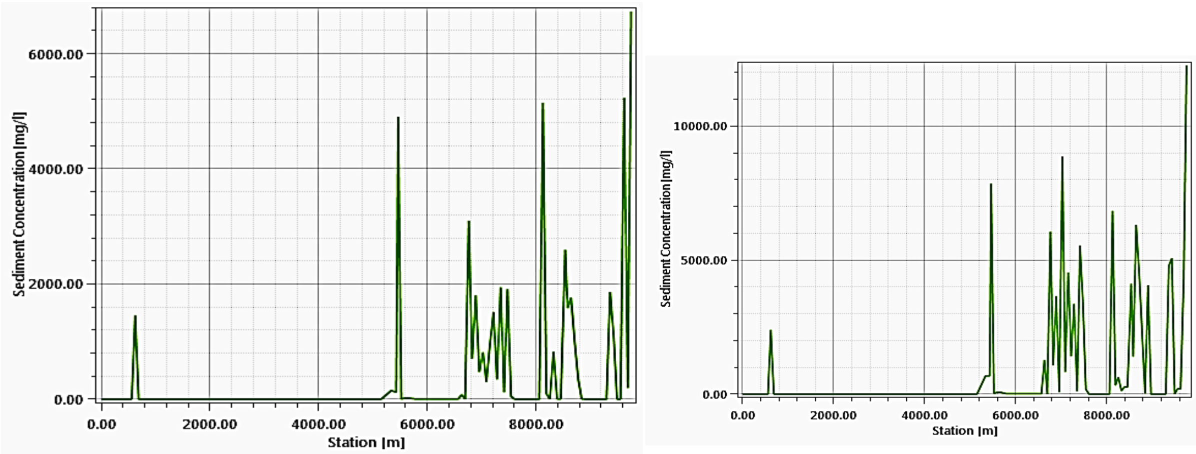

Figure 26. *Spatial sediment concentration variability (Example of: 23 January and 02 February 2016 floods)*

5 CONCLUSION

HEC RAS software was used to model solid transport at the Fodda Wadi dam reservoir. Once all of the parameters were set to within their useful ranges, the model worked as expected. The observation of the bed profile was chosen as a standard for contrasting the output of the model with the actual values that were observed. Also the R2, which is equal to 0,92, is the coefficient of determination that supported the validation. This demonstrates strong concordance between model predictions and actual data. We can therefore accept our model as suitable for simulating sedimentary transport in one dimension. The bathymetric levees at Algerian reservoirs are rarely performed. The employed method is especially useful for watersheds missing bathymetric data or without hydrometric stations upstream of dams.

ACKNOWLEDGEMENT

I would like to address a great thanks to the Algiers direction of dams and transfers (ANBT), to the chief of exploitation and all the staff of the Oued Fodda dam, who facilitated my access to the Oued Fodda dam and who put at my disposal all the necessary technical and operating data, and who accompanied me particularly, for the recovery of the samples of silt at the level of the dam and at the level of the wadis located upstream.

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Vol. 69 (2023), No. 2
pp. 160–178, ISSN 1802-5420
DOI 10.35180/gse-2023-0097