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Hydraulic and sediment transport simulation of Koiliaris River using the MIKE 21C model

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Abstract

The objective of this work is the simulation of the water depth, flow velocity and sediment transport in the downstream part of the Koiliaris River (Crete – Greece). The two-dimensional hydraulic model MIKE 21C is used, which has been developed specifically to simulate 2D flows and morphological changes in rivers. The model is based on an orthogonal curvilinear grid and comprises two parts: (a) the hydrodynamic part which is based on the Saint-Venant equations and (b) the morphological change part for the sediment transport. The curvilinear grid and bathymetry files were generated using a very high resolution DEM (1 m x 1 m). Time series discharge data from a hydrometric station and a 2D map of initial surface water elevation were also introduced as input parameters in the hydrodynamic part of the model. Regarding the sediment transport model, field measurements of the sediment characteristics and the suspended sediment concentration were used. The model was calibrated and verified using water level field data and sediment concentration data that were collected during high and low flow discharges. Model simulation was in good agreement with field observations as indicated by a variety of statistical measures. The results of the model were 2D maps of flow velocity, water depth, sediment transport and bed level changes. Using the obtained simulation results, extreme hydrological events such as droughts or floods transporting large sediment loads, can be monitored in the study area.

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Keywords: MIKE 21C model; hydraulic simulation; river morphology; flow depth; sediment transport

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1. Introduction

Various numerical models have been developed for river flow simulation and sediment transport, which solve the governing equations using certain computational algorithms. These models are divided into three main categories: one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) [7]. The most widely used, one-dimensional numerical models are mostly based on finite difference and finite element methods. Different software tools, such as the HEC River Analysis System model from the US Army Corps of Engineers [10] and the MIKE 11 hydraulic model developed at the Danish Hydraulic Institute [2], have been used extensively for the dynamic 1D flow simulation in rivers. One-dimensional models, although simple to use, fail to provide detailed information regarding the flow field. In contrast, two-dimensional modelling has the advantage of flow propagation simulation with great accuracy.

The purpose of this study was to simulate river flow and sediment transport with the 2D hydraulic model MIKE 21C. The main advantage of this model is that it is based on a curvilinear (boundary-fitted) grid where the grid lines follow the bank lines [3]. The curvilinear grid makes the MIKE 21C model a suitable tool for fast and detailed simulation of river hydraulics and sediment transport. A fine curvilinear grid also requires a high analysis elevation data file of the river bed. According to Horritt et al. [5], the most significant part in two - dimensional hydraulic simulations is the bathymetry representation that is the development of an accurate geometric description for the river channel. Therefore, the last few years, remote sensing systems are used, in order to have very high resolution DEM (topographic elevation) data [1]. In this work a high accuracy DEM of a spatial resolution 1 m x 1 m is used for the bathymetry representation.

2. Study area

The Koiliaris River Basin is located 15 km east of the city of Chania in Crete. The basin extends from the White Mountains, with highest altitude 2041m above sea level, to the coastline. The watershed has a total catchment area of 130 km^2 (Fig. 1).

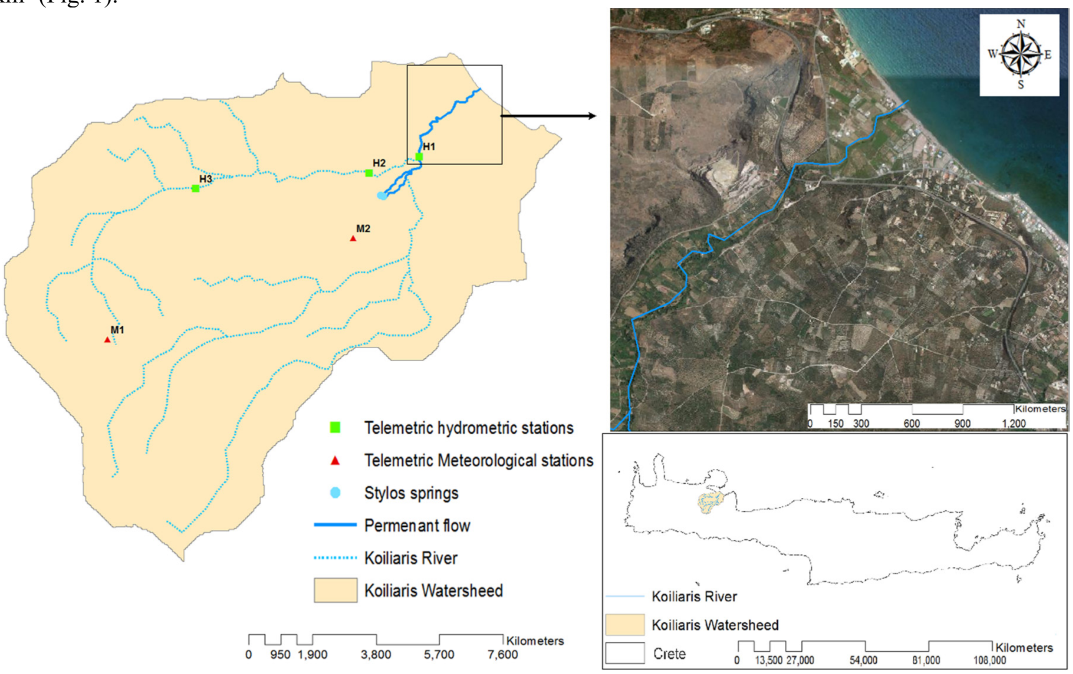

Fig. 1. Location of the Koiliaris River Basin and the downstream study area.

The Koiliaris River has two main temporary tributaries (Keramianos and Anavreti). The main volume of water in the Koiliaris River is discharged from the karstic system of the White Mountains through Stylos springs. Keramianos is the main tributary responsible for the bulk of the sediment transport in Koiliaris River, while water flows from the karstic springs have a relatively low concentration [9]. From the intersection point, where all the streams meet, to the outflow point the length of the river is 3.3 km.

In the Koiliaris River basin there are three telemetric hydrometric stations (H1, H2 and H3) and two telemetric meteorological stations (M1 and M2), which provide real-time data (Figure 1). For the present study, flux data from the hydrometric station of Agios Georgios (H1) is used to determine hydrological parameters

3. Methodology

3.1. The hydrodynamic module of MIKE 21C

MIKE 21C is a two-dimensional mathematical model for the simulation of water level, flow and sediment transport in rivers and estuaries. The hydrodynamic part of the model solves the vertically integrated Saint-Venant equations (continuity and conservation of momentum) in two directions [4]. The equations solved in MIKE 21C are:

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial s}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial n}\left(\frac{pq}{h}\right)+2\frac{pq}{hR_n}+\frac{p^2-q^2}{hR_s}+gh\frac{\partial H}{\partial s}+\frac{g}{C^2}\frac{p\sqrt{p^2+q^2}}{h^2}=RHS \qquad (1)$$

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial s}\left(\frac{pq}{h}\right)+\frac{\partial}{\partial n}\left(\frac{q^2}{h}\right)+2\frac{pq}{hR_s}+\frac{q^2-p^2}{hR_n}+gh\frac{\partial H}{\partial n}+\frac{g}{C^2}\frac{q\sqrt{p^2+q^2}}{h^2}=RHS \qquad (2)$$

$$\frac{\partial H}{\partial t}+\frac{\partial p}{\partial s}+\frac{\partial q}{\partial n}-\frac{q}{R_s}+\frac{p}{R_n}=0 \qquad (3)$$

Where s,n are the coordinates in the curvilinear coordinate system; p,q are the mass fluxes in the s and n direction, respectively; H is the water level; h is the water depth; g is the gravitational acceleration; C is the Chezy roughness coefficient; Rs and R_d are the radii of curvature of s- and n-lines, respectively; and RHS is the right hand side describing all of Reynold stresses

3.2. The sediment transport module of MIKE 21C

For the sediment transport the Engelund and Hansen (1967) formula was selected [4]. The Engelund and Hansen equation calculates the total load and divides this into bed and suspended load by the following equations.

$$S_{tl}=0.05\frac{C^2}{g}\theta^{5/2}\sqrt{(s-1)g{d_{50}}^3} \qquad (4)$$

$$S_{bl}=k_bS_{tl} \qquad (5)$$

$$S_{sl}=k_sS_{tl} \qquad (6)$$

Where S_{tl} is the total load; C is the Chezy number; θ is the Shields parameter; g is the acceleration of gravity; s is the relative density of the sediment; d_{50} is the median grain size; τ is the flow shear stress; ρ is the density of water; u is the flow velocity; S_{bl} is the bed load; S_{sl} is the suspended load; k_b is the fraction of bed load; k_s is the fraction of suspended load.

3.3. MIKE21C model set-up, calibration and validation

The most important process in the MIKE 21C model is the creation of a suitable curvilinear grid. To do this an accurate description of the bank lines is required, the coordinates of which can be derived from satellite images and cross section data. A dense curvilinear grid provides accurate simulations of the water flow. A bathymetry data file of the river bed is also required for the set-up of the model, using a very high resolution DEM (1m x 1m).

The hydraulic simulation was performed for the time periods 01/09/2010–31/08/2011 (calibration period) and 01/09/2011–31/08/2012 (validation period). As boundary conditions, hourly data of the flow were set. The hourly discharge time series was obtained from a hydrometric station at the upstream boundary of the river. Manning number and Eddy Viscosity were selected as model calibration parameters along the downstream river reach. The sediment transport module was calibrated and validated for the time period 01/09/2011–31/12/2013, when 16 samples of suspended sediment were collected at hydrometric station H1. Due to lack of measurements, for the boundary time series of suspended sediment concentration, a system of equation was developed based on the suspended sediment samples collected at station H1 and accumulated rainfall data from meteorological station M1, since rainfall is considered the main factor controlling the production and delivery of sediment in the area. Water discharge derived from the karstic springs has low sediment concentration, thus the discharge of the river cannot be correlated with the sediment transport. The coefficient for helical flow intensity and the dispersion coefficients in x and y directions were selected as calibration parameters for the suspended sediment transport model. The goodness of the calibration fit was tested against three statistical metrics proposed by Moriasi et al. [8]: the Nash–Sutcliffe Efficiency (NSE), Percent Bias (PBias), and RMSE Standard Deviation Error (RSR).

4. Results

4.1. Boundary Condition time series of suspended sediment concentration

A boundary condition time series of suspended sediment concentration was developed based on the suspended sediment samples collected at station H1 and accumulated rainfall data from meteorological station M1. It was observed that for low values of accumulated rainfall data (P) the regression equation was linear type (Eq.7) and for higher values the regression equation was power type (Eq. 8).

For $P < 10$ mm

$$SSC = 0.643 \cdot P + 2.917 \qquad R^2 = 0.92 \tag{7}$$

For $P \geq 10$ mm

$$SSC = 0.086 \cdot P^{2.067} \qquad R^2 = 0.84 \tag{8}$$

4.2. Grid and Bathymetry results

In the current study, a very dense curvilinear grid, of the downstream section of the Koiliaris River, was created using 1000 x 25 cells (Fig.2a). Then a bathymetry file, with only the coordinates and their heights above sea level, was created using a very high accuracy DEM (1m x 1m) and imported into the curvilinear grid. The result of the bathymetry file is described below in Fig. 2b

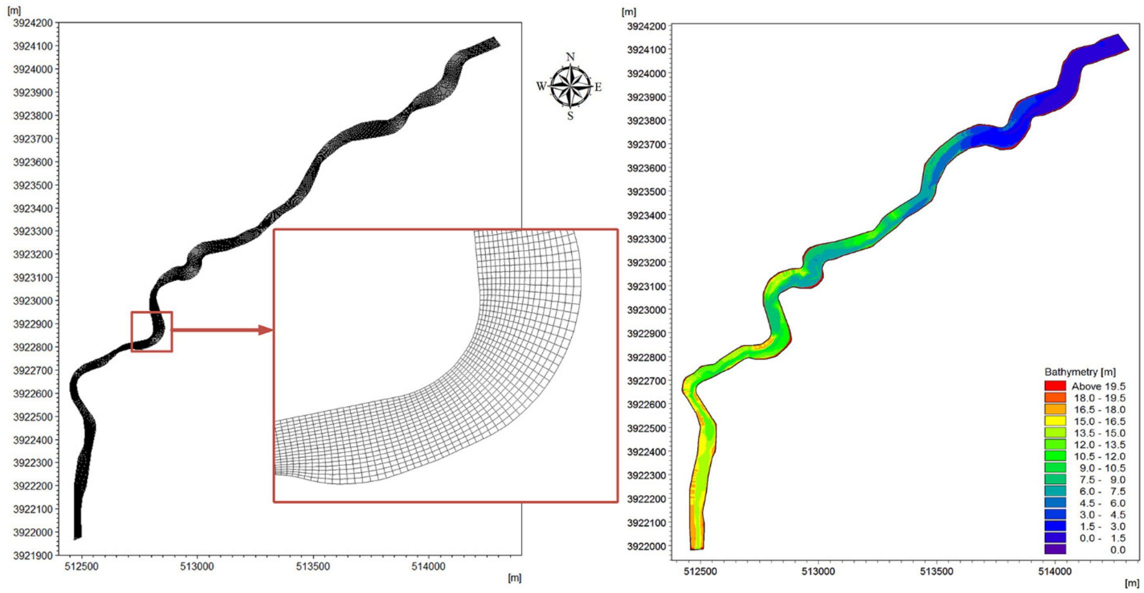

Fig.2. (a) The curvilinear grid, (b) The bathymetry file.

4.3. Calibration and Validation results

The calibration and validation process were performed estimating the Manning number (M) and Eddy Viscosity parameters for the HD model and the coefficient for helical flow intensity and the dispersion coefficients in x and y directions for the sediment transport model. The models were calibrated so that the model results to be in good agreement with the observed (water depth and suspended sediment concentration measurements) data at selected location H1. The hydrological system of the studied downstream river part is considered as a mass balance system without losses due to lack of measurements at the outlet point and taking into consideration the small river length. Thus, a downstream cross section with the same geometry as the one where the hydrometric station Agios Georgios is located was selected assuming that at this location the hydraulic characteristics such as water depth and sediment load have the same values with those at Agios Georgios station. The goodness of the fit is evident from the three statistical metrics: the Nash-Sutcliffe Efficiency (NSE), Percent Bias (PBias), and RMSE Standard Deviation Error (RSR) that presented in Table 1.

Table 1. Statistical metrics for the calibration and validation process

Statistical metric	Calibration time period	Validation time period
Hydrodynamic model		
Nash-Sutcliffe	0.88	0.87
RSR	0.35	0.35
Pbias (%)	-2.6	-8
Sediment transport model		
Nash-Sutcliffe	0.97	0.68
RSR	0.17	0.58
Pbias (%)	17.18	19.08

Fig. 3 depicts simulated values, at the outlet point of the studied river part, versus the observed data at Agios Georgios for the calibration and validation time periods taking into account a delay of 3 hours which is the mean flow travel time from upstream to downstream locations of the studied part of the Koiliaris River.

Manning number (M) varies across a river cross section. In this study, according to Kourgialas et al. [6] the river cross sections of Koiliaris River were divided in three zones with different bed resistance. The first zone represent the bottom of the river profile, the second represents the area close to banks and the third the overbanks zone. After the calibration process, the Manning number for each zone was found 25 $m^{1/3}/s$, 18 $m^{1/3}/s$ and 12.5 $m^{1/3}/s$ respectively, and the value of Eddy Viscosity was estimated at 0.1 m^2/s, the coefficient for helical flow intensity at the value of 0.4 and the dispersion coefficients at the value of 0.5 m^2/s.

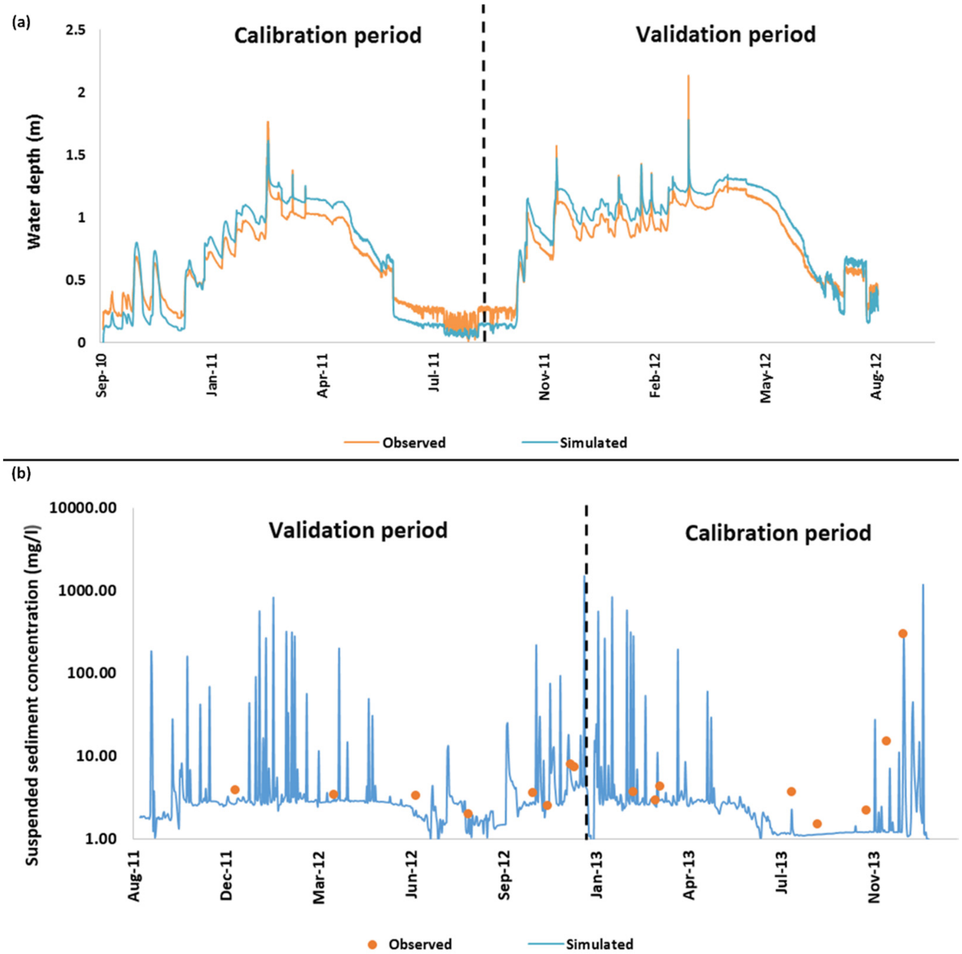

Fig. 3. Observed and simulated water depth and sediment concentration values, for the calibration and the validation time periods for (a) the Hydrodynamic model and (b) the sediment transport model.

4.4. Two-Dimensional result maps

The MIKE 21C model yields two-dimensional maps of water depth, flow velocity and suspended sediment concentration. Such maps for water depth were generated for two representative time steps of the simulation, 31/08/2011 (Fig. 4a) and 14/03/2012 (Fig. 4b). These time steps were selected demonstrating the low and high peak discharges of the dataset, respectively.

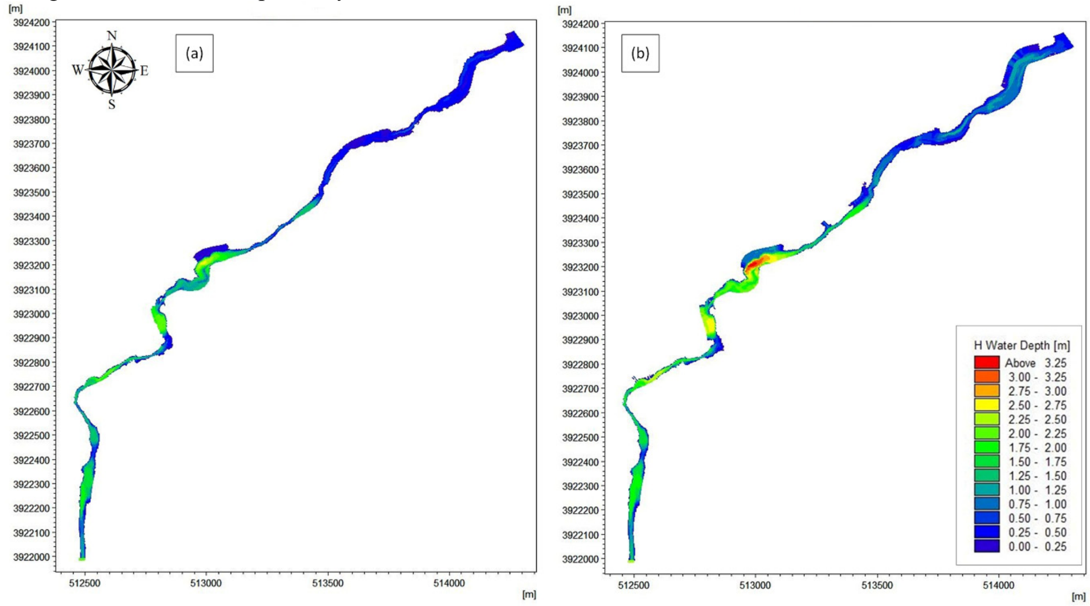

Fig. 4. 2D maps of water depth at the time step: (a) of lowest discharge (b) of the discharge peak

A 2D map of flow velocity and a 2D map of suspended sediment concentration also produced for the flow peak of 14/03/2012. These maps are illustrated in Fig. 5. The segments of the river that the velocity vectors are larger, in Fig. 5a, are the ones where the channel width is small or where the river geometry changes drastically. In Fig. 5b it is observed that after intense rainfall events, when Keramianos tributary carries large sediment loads, the concentration of suspended sediment in Koiliaris River can exceed the value of 500 mg/l.

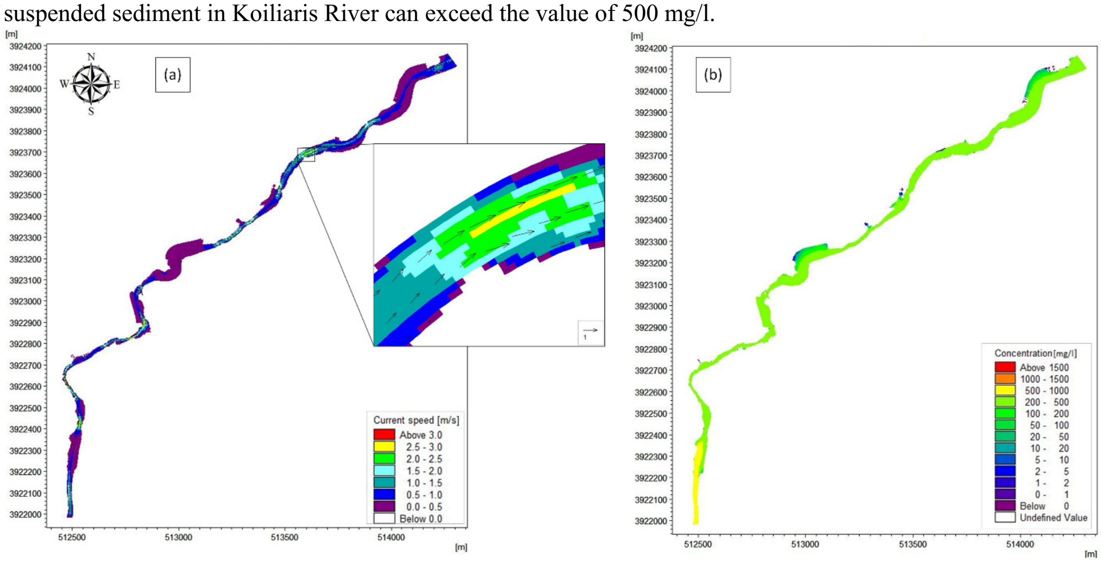

Fig. 5. 2D maps of (a) flow velocity and velocity vectors and (b) suspended sediment concentration at the time step of the discharge peak

5. Conclusions

The aim of this study was the hydraulic simulation of the flow velocity, flow depth and sediment transport of the Koiliaris River in Crete, Greece. A two-dimensional curvilinear grid hydraulic model was employed where the grid lines follow the bank lines of the river. Using a very dense curvilinear (boundary-fitted) grid and a bathymetry file with DEM in 1 m resolution provides a good flow analysis near the boundaries and thereby a high simulation accuracy of the water flow and sediment transport in the river. Regarding the calibration and verification processes, the hydraulic simulation results were in good agreement with the corresponding field measurements, with Nash – Sutcliffe coefficient taking values above 0.85 for both calibration and validation time periods. After the successful calibration and validation process, the 2D maps of water depth, of flow velocity vectors and sediment transport concentration were produced. By using the MIKE 21C simulation results, the hydraulic behavior and the flood hazard areas of the river can be specified. In addition, the model could be a useful tool for the prediction of the sediment transport and the morphology changes in the downstream part of the Koiliaris River.

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