River flow and sediment transport simulation based on a curvilinear and rectilinear grid modelling approach – a comparison study

G. G. Morianou, N. N. Kourgialas, G. P. Karatzas and N. P. Nikolaidis

ABSTRACT

In the present work, a two-dimensional (2D) hydraulic model was used for the simulation of river flow and sediment transport in the downstream section of the Koiliaris River Basin in Crete, Greece, based on two different structured grids. Specifically, an important goal of the present study was the comparison of a curvilinear grid model with a rectilinear grid model. The MIKE 21C model has been developed to simulate 2D flows and morphological changes in rivers by using either an orthogonal curvilinear grid or a rectilinear grid. The MIKE 21C model comprises two parts: (a) the hydrodynamic part that is based on the Saint-Venant equations and (b) the morphological change part for the simulation of bank erosion and sediment transport. The difference between the curvilinear and the rectilinear grid is that the curvilinear grid lines follow the bank lines of the river, providing a better resolution of the flow near the boundaries. The water depth and sediment results obtained from the simulations for the two different grids were compared with field observations and a series of statistical indicators. It was concluded that the curvilinear grid model results were in better agreement with the field measurements.

Key words | curvilinear grid, MIKE 21C model, rectilinear grid, river flow, sediment transport

INTRODUCTION

Several hydraulic models have been used for the simulation of river flow and sediment transport. These models are divided into four categories: (a) three-dimensional (3D), (b) two-dimensional (2D), (c) one-dimensional (1D), and (d) non-numerical hydraulic models. The 3D hydraulic models represent flow properties in the three directions, longitudinal–transversal–vertical. The 2D models represent flow properties along the longitudinal and the transversal directions. The 1D hydraulic models provide flow properties only in the downstream (longitudinal) direction. The fourth category is comprised of non-numerical hydraulic models, which includes field measurements, analytical solutions and statistical analysis of the flow field (Tonina & Jorde 2013). The most commonly used models are 1D. Several 1D models are available in the public domain; these include HEC-RAS (USACE 2002), Sedimentation and River Hydraulics 1D (Huang & Greimann 2010), FEQ (Franz & Melching 1997) and MIKE 11 (DHI 2007a). These models are simpler but fail to provide detailed information regarding the flow field. This limitation can be overcome by applying 2D and 3D models, which have the advantage of simulating flow propagation with great accuracy (Ghanem et al. 1996). Two-dimensional hydraulic modeling is currently a more affordable approach compared to 3D modeling because of its computational requirements (Shen & Diplas 2008). Widely used software packages for 2D modeling are the MIKE 21 (DHI 2007b; Vozinaki et al. 2012), the FLO-2D (O’Brien et al. 1993; Rickenmann et al. 2006), the TUFLOW (Alho & Mäkinen 2010; Baart et al. 2013).
it provides numerical results only at a finite number of points instead of cross-sections (as with a 1D approach). A set of such points, called nodes, forms a grid (or mesh) and defines the numerical domain which is an approximation of the physical domain (Tonina & Jorde 2013). Grids are grouped into structured and unstructured meshes. Structured grids have nodes arranged in an orderly fashion following an indexing pattern. They have typically quadrilateral (e.g. square and rectangular) cells with Cartesian or curvilinear coordinate systems (Geleynse et al. 2011). Unstructured grids may use triangles and 2D prisms in 2D grids and tetrahedrons, pyramids, hexahedrons and wedges or arbitrary polyhedrons or a combination of these in 3D grids (Lacey & Millar 2004; Hayes et al. 2007; Clark et al. 2008). An important difference between the two grid categories is that the finite difference method can only be applied to structured grids, in contrast to the finite element method, which can be applied both to structured and unstructured meshes (Oliveira et al. 2008). According to Cobby et al. (2003), 2D unstructured grids are commonly used to model flow fluctuations in lowland catchments (especially in floodplains). Channel elements describing the meandering river are usually discretized separately from those comprising the model floodplain and are most commonly represented by structured grids (Cobby et al. 2003).

Up to the present, a limited number of studies have considered the comparison of different types of computational meshes for hydraulic simulations and, in particular, for the simulation of sediment transport and bank erosion. Tonina & Jorde (2013) presented many examples of hydraulic models and their main features (computational mesh, discretization/equation and application), but there is no direct comparison of mesh performance for hydraulic models. The first direct comparison of two different, unstructured computational meshes, with the use of a finite element (TELEMAC-2D) model and a simple finite volume model, is performed in the study by Horritt et al. (2007). The main aim of the present work is the comparison, for the first time, of two different, structured computational meshes. Specifically, the purpose of this study is the simulation of the hydraulic behavior of a small-scale river by using a model that provides results on a curvilinear structured grid and a rectilinear structured grid. The MIKE 21C model (by DHI) has been developed for hydrodynamic and morphological change 2D simulations in rivers by using either an orthogonal curvilinear grid or a rectilinear grid. Hydraulic simulations are performed for the downstream section of the Koiliaris River, in Crete, Greece, using the two different grids of the MIKE 21C model. The comparison of the hydrodynamic and morphodynamic (sediment transport and bank erosion) results of the two different grids with field measurements takes place and the results of the two model approaches are tested against different statistical indicators. A preliminary comparison study of the performance of only the hydrodynamic module, using these two different orthogonal structured grids, was presented by Morianou et al. (2016b).

**STUDY AREA**

The Koiliaris River Basin is located in western Crete, 15 km east of the city of Chania. The basin extends from the White Mountains to the coastline and has a total catchment area of 130 km². The Koiliaris River Basin is a Mediterranean Critical Zone Observatory watershed. The total length of the Koiliaris River network is 36 km. The river has two temporary tributaries (Keramianos and Anavretis) and two permanent discharges from the White Mountains karstic system through the Stylos springs (Kourgialas & Karatzas 2013) (Figure 1). The Keramianos tributary drains a small, friable sub-basin and carries large sediment loads in the Koilairis River during intense rainfall events (Nerantzaki et al. 2015).

The main study area of this work is the river segment from the intersection point, where all the streams meet, to the outflow point. The topography of this area is smooth with a mild slope of 12% (Kourgialas et al. 2010) and the geology of the basin is mainly karst. There are three hydrometric stations and two telemetric meteorological stations in the Koiliaris River Basin. In the present study, hourly flow data from the hydrometric station of Ag. Georgios are used to determine hydrological parameters (Figure 1). Bank erosion measurements were performed in the area during a field campaign, which took place at the beginning of the hydrological year 2013–2014 (September 2013 to
February 2014). For this time period, four sediment concentration measurements were also available from the grab samples which were collected on a monthly basis at hydrometric station Ag. Georgios (Nerantzaki et al. 2015).

**METHODOLOGY**

The hydrodynamic module of MIKE 21C

The MIKE 21C is a 2D mathematical model for the simulation of water flow and sediment transport. The hydrodynamic part of the model solves the vertically integrated Saint-Venant equations (continuity and conservation of momentum) in two directions.

MIKE 21C hydrodynamic equations:

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

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

where \( s, n \) are the coordinates in the curvilinear coordinate system; \( p, q \) are the mass fluxes (kg·s\(^{-1}\)·m\(^{-1}\)) in the \( s \) and \( n \) directions, respectively; \( H \) is the water level (m); \( h \) is the water depth (m); \( g \) is the gravitational acceleration (m·s\(^{-2}\)); \( C \) is the Chezy roughness coefficient (m\(^{1/2}\)·s\(^{-1}\)); \( R_s \) and \( R_n \) are the radius of curvature (m) of \( s \)- and \( n \)-lines, respectively; and RHS is the right hand side describing all Reynolds stresses.

The river morphology module of MIKE 21C

There are several equations for the calculation of sediment transport in the MIKE 21C model. The Engelund & Hansen (1967) formula was used in this study (DHI 2013).

The Engelund and Hansen equation calculates the total load and divides it into bed and suspended load by the following equations:

\[
S_{tl} = 0.05 \frac{C^2}{g} \theta^{5/2} \sqrt{(\rho - 1)gd_{50}^3}
\]

\[
S_{bl} = k_0 S_{tl}
\]
\[ S_{sl} = k_s S_{sl} \]

where \( S_{sl} \) is the total load (kg \cdot s\(^{-1}\) \cdot m\(^{-1}\)); \( C \) is the Chezy number (m\(^{1/2}\) \cdot s\(^{-1}\)); \( \theta \) is the Shields parameter; \( g \) is the acceleration of gravity (m \cdot s\(^{-2}\)); \( \rho \) is the relative density of the sediment (kg \cdot m\(^{-3}\)); \( d_{50} \) is the median grain size (m); \( S_{sl} \) is the bed load (kg \cdot s\(^{-1}\) \cdot m\(^{-1}\)); \( S_{sl} \) is the suspended load (kg \cdot s\(^{-1}\) \cdot m\(^{-1}\)); \( h_b \) is the fraction of bed load; and \( k_s \) is the fraction of suspended load.

An important aspect of river morphological processes is bank erosion. In MIKE 21C, bank erosion (Equation (7)) is simulated in parallel with sediment transport and the hydrodynamic equations and at each time-step the eroded material is included in the solution of the sediment continuity equation (Equation (8)):

\[ E_b = -a \frac{\partial x}{\partial t} + \beta \frac{S}{h} + \gamma \]

\[ \Delta S_e = E_b \cdot (h + h_b) \]

where \( E_b \) is the bank erosion rate (m \cdot s\(^{-1}\)); \( z \) is the local bed level (m); \( S \) is the near-bank sediment transport (m\(^2\) \cdot s\(^{-1}\)); \( h \) is the local water depth (m); \( a \), \( \beta \) and \( \gamma \) are the calibration coefficients specified in the model; \( \Delta S_e \) is the extra sediment (m\(^2\) \cdot s\(^{-1}\)) which is included in the sediment continuity equation; and \( h_b \) is the height of the bank above the water level (m).

### The difference between the curvilinear and rectilinear grids

There is no difference between the curvilinear and rectilinear grid models in terms of the physical equations, but there is a difference in their solution in the grid. The curvilinear grid solves a set of elliptic partial differential equations (Equations (9) and (10)):

\[ \frac{\partial}{\partial s} \left( w \frac{\partial x}{\partial s} \right) + \frac{\partial}{\partial n} \left( w \frac{\partial x}{\partial n} \right) = 0 \]  

(9)

\[ \frac{\partial}{\partial s} \left( w \frac{\partial y}{\partial s} \right) + \frac{\partial}{\partial n} \left( w \frac{\partial y}{\partial n} \right) = 0 \]  

(10)

where \( x \) and \( y \) are the Cartesian coordinates, \( s \) and \( n \) are the curvilinear coordinates and \( w \) is a weight factor defined by

\[ w = \sqrt{\frac{x^2 + y^2}{x_h^2 + y_h^2}} \]

(11)

The boundary condition for this system is determined by

\[ x_n x_n + y_n y_n = 0 \]  

(12)

and

\[ f(x, y) = 0 \]  

(13)

where Equation (12) expresses the condition of orthogonality and Equation (13) expresses the location of grid points \((x, y)\) on a specific curve describing the boundary.

### MIKE 21C model set-up

The MIKE 21C model has been developed to simulate 2D flows and morphological changes in rivers by using either an orthogonal curvilinear grid or a rectilinear grid. The most important process in the MIKE 21C model is the creation of a suitable grid to cover the model area of the river. An accurate description of the bank lines is required for this purpose. For this study, the coordinates of the bank lines were derived from cross-section data. Next, a bathymetry data file of the river bed was inserted into the grid, in order to represent the mean bed level within grid cells.

The hydrodynamic modules for a curvilinear grid and a rectilinear grid were already calibrated for a time period of 20 days (11 November 2011–1 December 2011) by Morianou et al. (2016b). The Manning number (M) and eddy viscosity were used as model calibration parameters of the flow. The parameter of the model Manning M number is the inverse of Manning’s roughness coefficient (M = 1/n) (DH2 201b). More detailed information about the calibration processes of the two grid-models can be found in the study by Morianou et al. (2016b). In this work, a 6-month period (September 2013 to February 2014) was used for the validation process of the hydrodynamic module as well as for the calibration-validation processes of the morphodynamic
module of curvilinear and rectilinear grid-models. The results of these simulations were used to compare the efficiency of these two grid-models.

The hydrodynamic and morphodynamic modules were calibrated and validated so that the model results were in good agreement with the observed field data (water depth and sediment concentration). Since there are no field measurements for the outlet point, the hydrological system of the downstream river part under study is considered as a mass balance system without losses. This assumption takes into consideration the small river length as well as the uniform soil texture and riparian vegetation cover along the river line. Therefore, a downstream cross-section with geometry similar to that at the hydrometric station was selected based on the assumption that hydraulic characteristics such as water depth and sediment load have the same values at the two locations. A 3-hour delay, equal to the mean flow travel time from upstream to downstream locations in the Koiliaris River (Kourgialas et al. 2012) was also taken into account.

In this study, the time period from September 2013 to February 2014 was selected due to a field campaign (sediment concentration grab samplings and bank erosion measurements) which took place in the study area. The hourly data of the river flow, obtained from the hydrodynamic station of Ag. Georgios, were used as boundary conditions. The hydrodynamic module is validated using the calibrated values of Manning M and eddy viscosity, as were presented by Morianou et al. (2016b). The goodness of fit, both for hydrodynamic and morphodynamic modules, was tested against three statistical metrics proposed by Moriasi et al. (2007): the Nash–Sutcliffe efficiency (NSE), percent bias (PBias), and root mean square error–observations standard deviation ratio (RSR).

The morphodynamic module of the model is calibrated using sediment concentration field data for the time period from September 2013 to February 2014. In this time period, four sediment concentration grab samplings were available. Since sampling during high flows was difficult, only one sample with high sediment concentration (300 mg/l) was obtained (4 December 2013) by Nerantzaki et al. (2015). Due to the lack of sediment concentration time series, a system of equations was developed based on the field suspended-sediment samples from the hydrometric station and rainfall data from a meteorological station in the area (Morianou et al. 2016a). The coefficient for helical flow intensity, the dispersion coefficients in the x and y directions and the calibration bank-erosion coefficients α, β and γ in Equation (7) are used as calibration parameters for the morphodynamic module and the goodness of the calibration fit is tested against the three statistical metrics proposed by Moriasi et al. (2007).

The validation process of the morphodynamic module is performed, in the same time period as the calibration process, using bank erosion field measurements from the field campaign (Varouchakis et al. 2016). Thus, a point located in a river meander (point E1) and a point located at the straight line of the channel (point E2) were used for the validation process. The bank erosion at the first location was measured at a value of 0.3 m and at the second location at a value of 0.02 m.

RESULTS AND DISCUSSION

Grid and bathymetry results

A dense grid of the downstream section of the Koiliaris River was created using 1,000 × 25 cells. Next, a bathymetry file, with only the coordinates and the heights above sea level (ASL), was created using a very high accuracy DEM (digital elevation model, 1 m × 1 m) (Vozinaki et al. 2016) and imported into the grid (Figure 2(a)). The model requires also a true land value; all grid points with elevation greater than or equal to this value will always be considered as land and will not be subject to possible flow simulation. The true land value was set at 20 m (ASL).

The difference between a rectilinear and a curvilinear grid is depicted in Figure 2. The grid lines of the curvilinear grid follow the bank lines of the river, providing a better resolution of the flow near the boundaries than a rectilinear grid. The rectilinear and curvilinear grids for a segment of the Koiliaris river bank are shown in Figure 2(b) and 2(c), respectively. An example of the cell forms for the rectilinear and curvilinear grids given by the DHI user manual (DHI 2011) is presented in Figure 2(d) and 2(e), respectively.
Flow, sediment and bank erosion results

For the comparison of the curvilinear grid model and of the rectilinear grid model with the field observations, water field and sediment concentration data from the hydrometric station of Ag. Georgios and bank erosion measurements for a 6-month period (September 2013–February 2014) were used. The validation results of the hydrodynamic module, with the simulated hourly water depth values versus the observed water depth data are shown in Figure 3(a) for the rectilinear grid model and in Figure 3(c) for the curvilinear grid model. The calibration results of the morphodynamic module, with the simulated sediment concentration values versus the corresponding field data are presented in Figure 3(b) and 3(d), for the rectilinear and curvilinear grid models, respectively. Three statistical metrics were also calculated for the comparison of the two models with the field measurements: the NSE, the RSR and the PBias (%).

The model performance can be evaluated as ‘satisfactory’ if NSE > 0.50, RSR < 0.70 and if Pbias < ±25% for streamflow and Pbias < ±55% for sediment. Positive values of Pbias indicate model underestimation of bias, and negative values indicate model overestimation of bias. In this study, we consider ‘very good’, ‘good’ and ‘satisfactory’ ratings performance according to the evaluation of range values by Moriasi et al. (2007). The recommended values for adequate model simulation are within the ‘good’ and ‘very good’ performance ratings. The determination index ($R^2$) was also calculated in order to demonstrate the goodness of the hydrodynamic module validation ($R^2 = 0.896$) and of the morphodynamic module calibration ($R^2 = 0.998$) of the rectilinear grid model (Figure 3(a) and 3(b)) and of the curvilinear grid ($R^2 = 0.909$ and $R^2 = 0.999$, respectively) (Figure 3(c) and 3(d)).

After the calibration process of the morphodynamic module, the value of the coefficient for helical flow intensity was estimated at 0.4, the value of the dispersion coefficients at 0.5 m$^2$/s and the bank-erosion calibration factors $\alpha$, $\beta$ and $\gamma$ were estimated at 10, 0.01 and 0, respectively.

During the validation process of the morphodynamic module, for the curvilinear grid model, the simulated value of bank erosion at location E1 (meander) reached a field...
measurement value of 0.3 m while the simulated value at location E2 reached a value of 0.01 m compared to the measured value of 0.02 m (Figure 4(a)). The simulated values of bank erosion obtained from the rectilinear grid model are presented in Figure 4(b). A large deviation is observed between the simulated riverbank erosion values obtained from the rectilinear grid model and those obtained from the curvilinear grid model (Figure 4). This is also evident from the difference between the simulated value at point E1 (1.10 m) and the field measurement at the same point (0.30 m) (Figure 4(b)). Thus, the validation process of the morphodynamic module in the rectilinear grid model fails to reproduce the field observations.

As indicated by the results, in the case of the curvilinear grid model, the simulated values of water depth and sediment concentration are in good (very good, in many cases) agreement with the field data. In the case of the rectilinear grid model, the agreement between simulated values and field data is not as good as in the former case, but still the performance rating is satisfactory (Table 1 and Figure 3). However, great differences are observed between the two models, for the validation process of the morphodynamic module, in the bank erosion simulation. These discrepancies arise from the main difference between the two grids. One of the most difficult tasks in hydraulic simulation is the development of an accurate geometry of the river sections that follow the water flow path (Abate et al. 2015). Based on the results of this study, it is evident that the lines of the curvilinear grid which follow the bank lines of the river provide a better resolution of the sediment transport and the bank

![Figure 3](images/figure3.png)
erosion at the boundaries – riverbanks (Figure 4). Therefore, it is beneficial for an accurate simulation to use curvilinear grids for the simulation of sediment transport and riverbank erosion.

It was also observed, during simulations, that the rectilinear grid model required a smaller computational time-step in order to create stable conditions in the model, and thus greater computation time (20 hours compared to 2 hours for the curvilinear grid model) and larger storage capacity.

**CONCLUSIONS**

In this study hydraulic simulations were performed for the downstream section of the Koiliaris River. The 2D hydraulic model MIKE 21C was utilised in order to simulate the river flow, the sediment transport and the bank erosion with two different orthogonal structured grids. A comparison of the hydraulic modeling results (water flow and sediment transport both in high and low discharges), from the two different grids, was performed. The use of high-resolution topographic data was crucial for the development of a detailed bathymetry file.

Regarding the comparison of the results, the water depth and the suspended sediment concentration were generally in good agreement with the corresponding observations.
for both models. The Nash–Sutcliffe coefficient had a value of 0.68 for the hydrodynamic module and a value of 0.97 for the morphological module during the curvilinear grid-based simulation. For the same modules, the rectilinear grid-based simulation gave Nash–Sutcliffe coefficient values of 0.61 and 0.76, respectively. The simulations in the curvilinear grid model showed better performance than in the rectilinear grid, especially for the morphodynamic module. In addition, the rectilinear grid-based simulation provides very high riverbank erosion values and fails to reproduce the field observations. Since river channel geometry is the most significant input in the hydraulic simulation, the accurate description of riverbank lines provided by a curvilinear grid shows better hydraulic results. Furthermore, the curvilinear grid model requires less computational time and creates smaller files in memory.

This study indicates that the curvilinear grid provides a better flow analysis near the boundaries (riverbanks) and thereby a higher simulation accuracy of the water flow and sediment transport in the river. Therefore, it is effective to use curvilinear grid models, especially for the simulation of sediment transport and riverbank erosion.

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