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Comparison between curvilinear and rectilinear grid based hydraulic models for river flow simulation

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Abstract

In the present work, the two-dimensional hydraulic models MIKE 21 and MIKE 21C were used in order to simulate the water depth at the downstream section of the Koiliaris River Basin in Crete-Greece. Specifically, an important goal of the present study was the comparison of the widely used MIKE 21 with the MIKE 21C model. The MIKE 21C model has been developed specifically to simulate 2D flows and morphological changes in rivers. It is based on an orthogonal curvilinear grid and 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 sediment transport. In contrast to model MIKE 21C, the general version of MIKE 21 is based on a rectilinear grid. 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 results of the two models were compared with field observations and a series of statistical indicators. It was concluded that the curvilinear grid based model results were in better agreement with the field measurements.

Peer-review under responsibility of the organizing committee of the EWaS2 International Conference on Efficient & Sustainable Water Systems Management toward Worth Living Development

Keywords: MIKE 21C model; MIKE 21 model; curvilinear grid; rectilinear grid

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1. Introduction

Several hydraulic models have been used for the simulation of river flow. The most commonly in use are the one-dimensional models, which are simpler to use but fail to provide detailed information regarding the flow field. This limitation can be overcome by applying the two-dimensional models. Widely used software packages for 2D modelling are the MIKE 21 model [2, 9] and the FLOW 2D model [8]. Two-dimensional modelling has the advantage of flow propagation simulation with great accuracy. Nevertheless, 2D models require substantial computational time and a fine river grid. The purpose of this study was to simulate river flow by using a curvilinear grid based model (MIKE 21C) in comparison to a rectilinear grid model (MIKE 21).

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 to the coastline and has a total catchment area of 130 km^2. The total length of the Koiliaris River network is 36 km. The river has two temporary tributaries and two permanent discharged from the karstic system of the White Mountains through Stylos springs (Fig. 1). From the intersection point, where all the streams meet, to the outflow point the length of the river is 3.3 km. The topography of the study area is smooth with a mild slope of 12% [5] and the geology of the basin is mainly karst with quaternary–neogenic deposits and flysch formations. In the Koiliaris River basin, there are three telemetric hydrometric stations. For the present study, flow data from the hydrometric station of Agios Georgios are used to determine hydrological parameters.

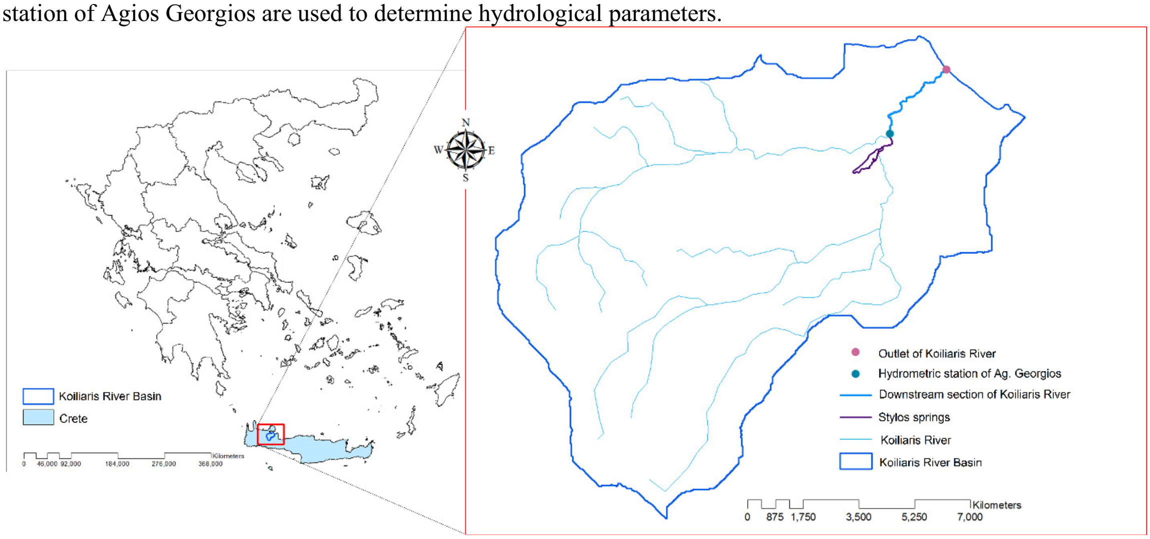

Fig. 1. Location of Koiliaris River Basin

3. Methodology

3.1. MIKE 21 & MIKE 21C hydrodynamic equations

MIKE 21 and MIKE 21C are two-dimensional mathematical models for the simulation of water flow and sediment transport. The hydrodynamic part of the models solves the vertically integrated Saint-Venant equations (continuity and conservation of momentum) in two directions. Eq. 2, 3 & 4 describe the MIKE 21 HD model [2] and Eq. 4, 5 & 6 describe the MICE 21C HD model [4].

MIKE 21 hydrodynamic equations

$$\frac{\partial P}{\partial t}+\frac{\partial}{\partial x}\left(\frac{P^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{PQ}{h}\right)+gh\frac{\partial H}{\partial x}+\frac{g}{C^2}\frac{P\sqrt{P^2+Q^2}}{h^2}=RHS \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{PQ}{h}\right)+\frac{\partial}{\partial y}\left(\frac{Q^2}{h}\right)+gh\frac{\partial H}{\partial y}+\frac{g}{C^2}\frac{P\sqrt{P^2+Q^2}}{h^2}=RHS \tag{2}$$

$$\frac{\partial H}{\partial t}+\frac{\partial P}{\partial x}+\frac{\partial Q}{\partial y}=0 \tag{3}$$

MIKE 21C hydrodynamic equations

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial s}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial n}\left(\frac{pq}{h}\right)+2\frac{pq}{hR_n}+\frac{p^2-q^2}{hR_s}+gh\frac{\partial H}{\partial s}+\frac{g}{C^2}\frac{p\sqrt{p^2+q^2}}{h^2}=RHS \tag{4}$$

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial s}\left(\frac{pq}{h}\right)+\frac{\partial}{\partial n}\left(\frac{q^2}{h}\right)+2\frac{pq}{hR_s}+\frac{q^2-p^2}{hR_n}+gh\frac{\partial H}{\partial n}+\frac{g}{C^2}\frac{q\sqrt{p^2+q^2}}{h^2}=RHS \tag{5}$$

$$\frac{\partial H}{\partial t}+\frac{\partial p}{\partial s}+\frac{\partial q}{\partial n}-\frac{q}{R_s}+\frac{p}{R_n}=0 \tag{6}$$

Where x,y are the Cartesian coordinates; P, Q are the mass fluxes in the x and y direction, respectively; 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 Rd are the radii of curvature of s- and n-lines, respectively; and RHS is the right hand side describing all of Reynold stresses

The general version of MIKE 21 is based on a rectilinear grid for simulations of open sea and coastal applications. However, in river applications an accurate resolution of the boundaries is required which necessitates the use of curvilinear grids. The benefits of using a curvilinear computational grid are visualized in Fig. 2 where a river reach is represented by both grids. The curvilinear grid (MIKE 21C) requires fewer computational points and, thus, smaller storage capacity than the rectilinear grid (MIKE 21), providing at the same time a better resolution of the flow near the boundaries [3].

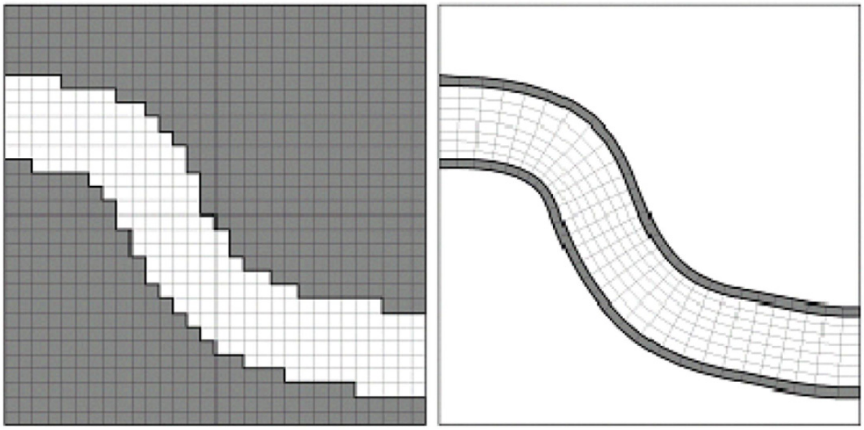

Fig. 2. Left: A rectilinear grid (MIKE 21 model). Right: A curvilinear grid (MIKE 21C model), by MIKE 21C, 2011, User Guide

The curvilinear grid is constructed by the grid generator, which solves a set of elliptic partial differential equations (Eq. 7 & 8).

$$\frac{\partial}{\partial \xi}\left(g\frac{\partial x}{\partial \xi}\right)+\frac{\partial}{\partial \eta}\left(g\frac{\partial x}{\partial \eta}\right)=0 \tag{7}$$

$$\frac{\partial}{\partial \xi}\left(g\frac{\partial y}{\partial \xi}\right)+\frac{\partial}{\partial \eta}\left(g\frac{\partial y}{\partial \eta}\right)=0 \tag{8}$$

Where x and y are the Cartesian coordinates, and g is a weight factor defined by

$$g=\sqrt{\frac{x_\xi^2+y_\xi^2}{x_\eta^2+y_\eta^2}} \tag{9}$$

The boundary condition for this system is the non-linear orthogonality condition

$$x_\xi x_\eta + y_\xi y_\eta = 0 \tag{10}$$

$$f(x,y)=0 \tag{11}$$

Where (Eq. 10) expresses the condition of orthogonality and (Eq. 11) expresses the location of grid points (x, y) on a specific curve describing the boundary. Therefore, there is no difference between the curvilinear and rectilinear grid based models in the physical equations, but in their solution in the grid.

3.2. MIKE 21C – curvilinear grid model set-up

The most important process in the MIKE 21C model is the creation of a suitable curvilinear grid [1]. To do this an accurate description of the bank lines is required, the coordinates of which was 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.

The model was calibrated for the time period 11/11/2011 - 01/12/2011. As boundary conditions, hourly data of the flow were set from the hydrodynamic station of Agios Georgios. Manning number coefficient and Eddy Viscosity were selected as model calibration parameters. Manning number (M) is used to describe the resistance to flow due to channel roughness caused by sand or gravel bed, bank vegetation and other obstructions. The Eddy Viscosity represents the molecular viscosity and the effects of turbulence from the Reynold's stress terms. These two factors can affect the water surface profile of a river simulation. The goodness of the calibration fit was tested against three statistical metrics proposed by Moriasi et al [7]: the Nash–Sutcliffe Efficiency (NSE), Percent Bias (PBias), and RMSE-observations standard deviation ratio (RSR).

3.3. MIKE 21 – rectilinear grid model set up

The parameters of the hydrodynamic model MIKE 21 were identical to those introduced in the hydrodynamic model MIKE 21C after the calibration, except the bathymetry file which was imported into a rectilinear grid. The rectilinear grid requires equidistant grid spacing in the x- and y- direction and thus the resulting grid will be a rectangle resolved with rectangular elements.

4. Results

4.1. Bathymetry results

In the current study, a dense curvilinear grid, of the downstream section of the Koiliaris River, was created using 1000 x 25 cells. Then a bathymetry file, with only the coordinates and their heights above sea level, was created using a very high accuracy DEM (1 m x 1 m) and imported into the curvilinear grid (Fig. 3) and then into a rectilinear grid (Fig. 4).

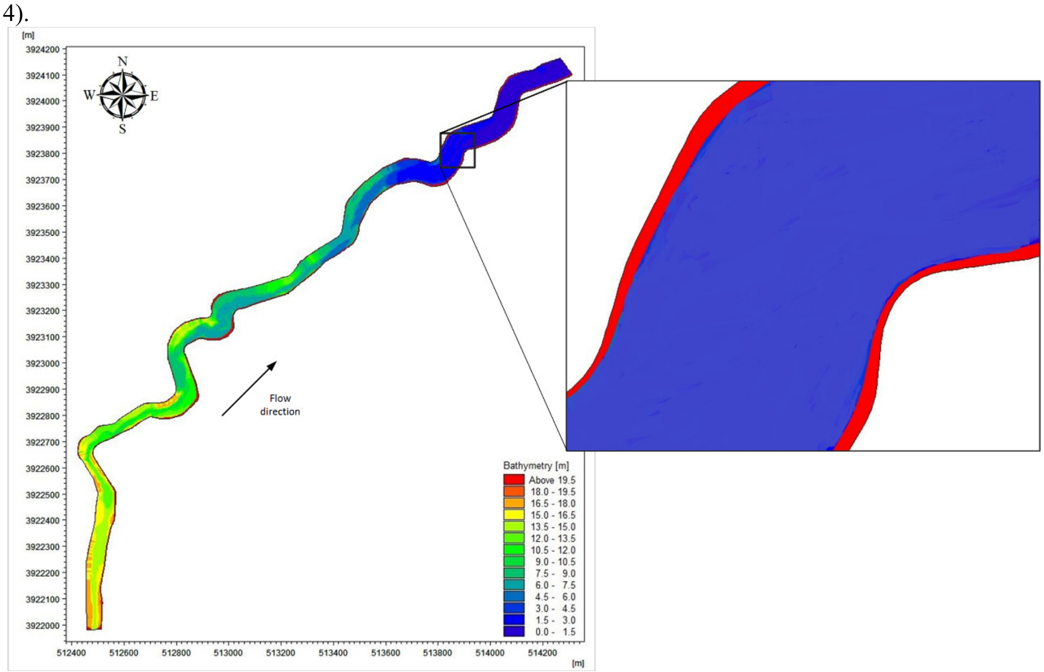

Fig. 3. Bathymetry file imported into a curvilinear grid.

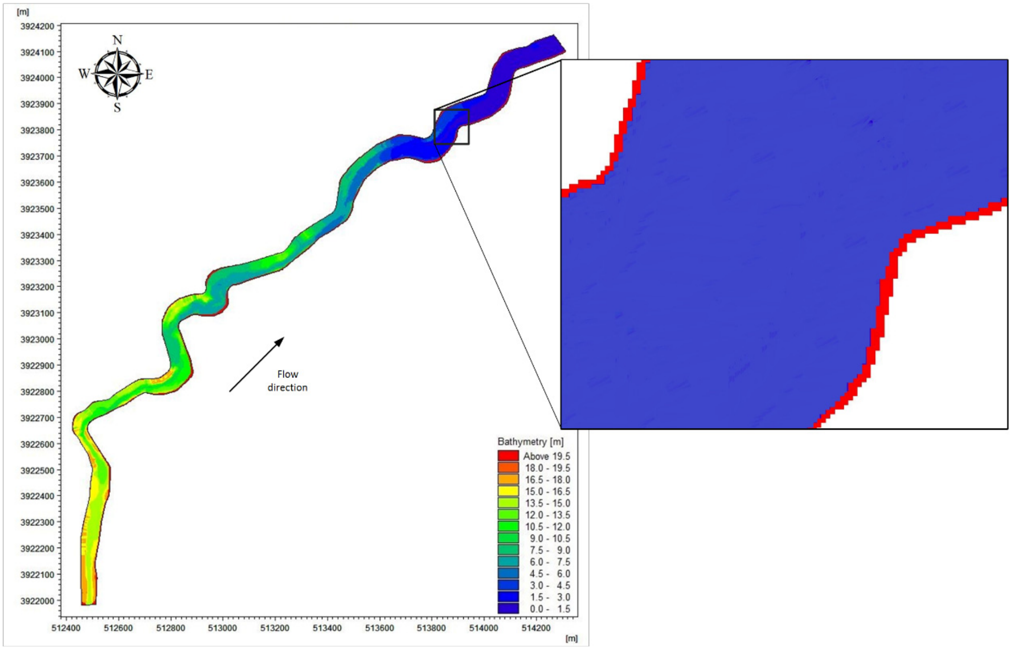

Fig. 4. Bathymetry file imported into a rectilinear grid

4.2. Calibration results

The calibration process were performed estimating the Manning number and Eddy Viscosity parameters so that the model results to be in a good agreement with the observed (water depth measurements) data. For the comparison of the curvilinear grid model (MIKE 21C) and of the rectilinear grid model (MIKE 21) with the field observations, water field data from the hydrometric station of Agios Georgios for a time period of 20 days was used. This time period was chosen as a representative time period with very low and very high discharges. Fig. 5 depicts simulated water depth versus the observed data at Agios Georgios for the calibration period of the two models. Three statistical metrics were also calculated for the comparison of the two models with the field measurements: the Nash-Sutcliffe Efficiency (NSE), the RSR and the PBias (%). For the curvilinear grid model (MIKE 21C) the NSE was 0.71, RSR 0.53 and PBias -4.09 and for the rectilinear grid model (MIKE 21) the NSE was -7.6 (unsatisfactory performance rating), RSR 2.92 and PBias -23. It is evident from Fig. 5 and the statistical indicators, that the performance of model MIKE 21C is much better than the one of MIKE 21.

Manning number (M) varies across a river cross section [6]. After the calibration process, the Manning number for the first zone, which represents the bottom of the river profile, was found 25 $m^{1/3}/s$, for the second zone, which represents the area close to banks, was found 18 $m^{1/3}/s$ and for the third zone which represents the overbank area was found 12.5 $m^{1/3}/s$. The value of Eddy Viscosity was estimated at $0.1 m^2/s$.

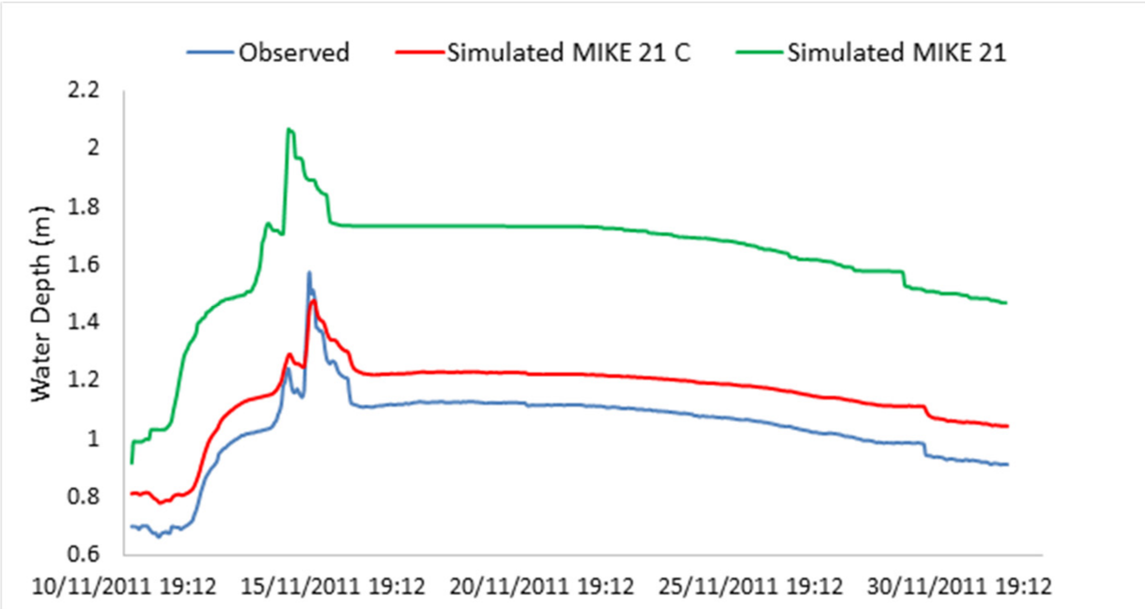

Fig. 5. Simulated values of water depth by MIKE 21 C model (red color), by MIKE 21 model (green color), compared to the observed values (blue color).

5. Conclusions

The aim of this study was the comparison of a curvilinear grid based model with a rectilinear grid based model. The difference between the two grids is that the grid lines of the curvilinear grid follow the bank lines of the river, providing a better resolution of the flow near the boundaries. The water depth results of the two models compared with the field observations and three statistical metrics proved that the curvilinear grid based model results were in better agreement with the field measurements. On the other hand, the rectilinear requires a smaller computational time step in order to create stable conditions in the model, and thus greater computing time (20 hours versus 2 hours for the curvilinear grid model) and larger storage capacity.

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