Bathymetry interpolation for hydrodynamic modelling

N. Basos(1), **F. Martins**(1) **and J. Rodrigues**(2)
(1) Universidade do Algarve. nadyabasos@i.ua,
(2) Universidade do Algarve, CIMA

Abstract: Estuarine hydrodynamic models require management of large quantities of georeferenced information. Good quality of the spatial input data is critical for obtaining realistic model results. GIS is the most appropriate tool to process that data. In this work GIS tools were used to pre-process the model grid and bathymetry for simulating the hydrodynamics of the Guadiana Estuary. Bathymetry data were interpolated to a curvilinear grid using several different methods, including an advanced river straightening method (transformation to the along-channel coordinate system). The finite volume model MOHID with 2D configuration was used to test these methods and evaluate the associated improvements. The use of bathymetry interpolated in the channel-oriented coordinates significantly improved the direction of the water current and slightly improved the velocity modulus values. The use of GIS tools to produce model inputs proved to be a valuable aid to coastal hydrodynamic modelling increasing the model accuracy.

Key words: GIS, bathymetry interpolation, hydrodynamic model, Guadiana Estuary

1. INTRODUCTION

Estuarine hydrodynamic models always require management of large amounts of georeferenced information. Geographic information systems (GIS) can provide powerful support for numerical water modelling. In particular, GIS can help to manage, analyze and display the model spatial data. Recently, many attempts to couple GIS and hydrodynamic models are described in the literature (Naoum *et al.*, 2005; Green and King, 2003). However, most of the developers took advantage mainly from visualization capabilities of GIS, but not from advanced GIS tools for increasing the model accuracy. Good quality of the spatial input data is critical for obtaining realistic model results. Merwade *et al.* (2008) and Merwade *et al.* (2005) have discussed improving hydrodynamic model accuracy with GIS techniques by using advanced interpolation of bathymetry data for river models. The proposed method used interpolation of river cross-sections in a channel-fitted coordinate system. For that study only simple cross-validation of the interpolation was performed but no hydrodynamic model was run (Merwade *et al.*, 2008). The present study complements that methodology by real model runs. MOHID is an open-source water modelling system supporting GUI modules for model pre- and post-processing (Braunschweig *et al.*, 2004). MOHID Water module simulates flow in surface water bodies in 3D using the Finite Volume method (Martins *et al.*, 2001). For running a hydrodynamic model MOHID needs gridded (spatially discretized) bathymetry and forcing (water discharges and tide). Gridded bathymetry is a key spatial input requiring spatial data of high quality. MOHID GIS module can interpolate bathymetry point data into a computational grid, using land polygon presenting non-computing areas. In a case of a curvilinear grid, firstly a water domain polygon is needed to generate the grid.

2. CASE STUDY

The Guadiana Estuary is a narrow rock-bound estuary located between Portugal and Spain. It extends for 80 km from the mouth upstream and is prolonged offshore by a submerged delta. The estuary has an average depth of about 5 m with maximum depths up to 18 m. At spring tide and low river discharge, the estuary is well-mixed. But at neap tide it is partially stratified (Garel *et al.*, 2009). The bathymetry data for the model were used from many sources (Basos, 2013). The available datasets were transformed into one coordinate system and converted into shapefiles. The data points also were clustered in a case of too dense point distribution, and joined into one dataset for future interpolation, which had about 130 000 points (Basos, 2013). The missing bathymetry data in some very shallow parts of the estuary were estimated from the orthophoto by statistical methods (Basos *et al.*, 2012, Basos, 2013). The points along the shoreline at the lower estuary were added with 0 depth value. The shoreline (water domain) was extracted from the orthophoto by image classification based on PCA of the spectral bands (Basos, 2013). A boundary-fitted curvilinear was selected for modelling the Guadiana Estuary. MOHID GIS can generate structured nearly-orthogonal curvilinear grids using a water domain polygon following the shoreline. The water polygon was imported into MOHID GIS and the curvilinear grid was generated in this domain (Basos *et al.*, 2012). The final grid dimensions were 2209x122 cells and the cell size varied from 10 m to 70 m inside the estuary and up to 300 m at the submerged delta. This grid was used to produce a gridded bathymetry using interpolation of data points into the grid cells.

3. BATHYMETRY INTERPOLATION

There are many studies dedicated to interpolation of bathymetry data. Most of them conclude that the best accurate method is kriging, some works suggest spline with tension (minimum curvature) and IDW methods (Medved *et al.*, 2010). There were also successful attempts to use ANUDEM method for producing bathymetry (Daniell, 2008), which is applied as Topo to Raster method in ArcGIS software. MOHID GIS uses linear Triangulation method for grid cell centers (Basos, 2013). For interpolation of bathymetry points for the Guadiana Estuary several methods using MOHID GIS 4.9.2, ArcGIS 9.3 and Surfer 10 were tested to find the best suited for the estuary. Topo to Raster interpolation was performed using Spatial Analyst in ArcGIS with no drainage enforcement. Kriging was performed using Geostatistical Analyst in ArcGIS in the two ways. The first attempt was isotropic (a spherical model with sill 4.5 and range 200 m, the second order trend removal). But it was obvious from the semivariogram that the data had anisotropy (figure 1).

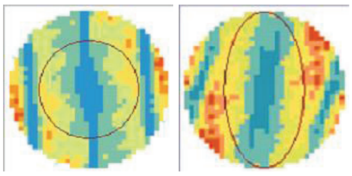

Figure 1. Semivariogram/Covariance Surface for kriging in XY coordinates (left) and in RM coordinates (right, explained below).

The bathymetry changes more slowly in the north-south direction, in general. So, the second kriging model was spherical with anisotropy angle 80 degrees, major range 200 m and minor 300 m.The interpolations were performed with cell size of 5 m. Then every interpolated raster was overlaid by the curvilinear grid polygons. Using the *Zonal statistics* tool in ArcGIS, the average values of raster cells located inside each curvilinear cell were calculated, then attached to curvilinear cell centers and imported into MOHID as model input bathymetries. IDW with different powers, triangulation and natural neighbour interpolations showed not very good, crude and unrealistic results for the estuary. Minimum curvature and kriging produced better results, and Topo to Raster the most realistic. However, it was visible on the resulting surfaces that all isotropic interpolations had artefacts on the surfaces, such as unreal hills and deep holes along the channel (figure 2). These errors occurred due to highly irregular distribution of the survey points along the ship tracks. Isotropic interpolations assume circular influence of each point. But kriging with N-S anisotropy showed not good result as well. Despite the improved bottom in the north-south aligned parts of the estuary, it produced much worse result in the curved parts of the channel which are not aligned in that direction. The red arrow in figure 2 shows one of the east-west parts of the channel where all interpolations interrupted the deep channel, producing unexisting shallow barriers and artificial hills on the shoreline. The anisotropic kriging produced even the worst result in this place. It was clear that common methods cannot interpolate a curved long estuary correctly, because anisotropy of river bottom is variable and follows the river centerline (namely, the thalweg). Bathymetry usually changes very slowly along the centerline and rather quickly across-channel. Wadzuk and Hodges (2001) firstly proposed a methodology for straightening a sinuous river. They assumed converting the Cartesian coordinates X,Y into R(X,Y) and M(X,Y) coordinates, where M is the distance along the river centerline for any point and R is the perpendicular distance of this point from the centerline.

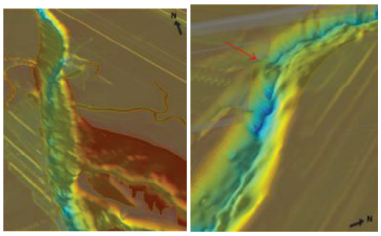

Figure 2. Kriging spherical (left) and with N-S anisotropy (right) bathymetry interpolation. The red arrow points on the unexisting shallow barrier.

Thus, a curved river can be transformed into a straight river by mapping the points in R and M coordinates (figure 3). Interpolation and other processing can be performed in this transformed RM space. Then, all the points can be transformed back to the original coordinates, so the original geometry is not affected (Merwade *et al.*, 2005). However, this back-transformation is mathematically quite complicated and cannot be done easily in GIS environment. This methodology was improved by Merwade *et al.* (2005), Merwade *et al.* (2006) and Merwade *et al.* (2008), who also compared several interpolation methods and found (using cross-validation) that anisotropic methods, after transformation into RM coordinates, performed significantly better interpolation results than regular isotropic methods (Merwade *et al.*, 2006). So, for obtaining realistic interpolation of the Guadiana estuary the bathymetry points were transformed into R,M space and there interpolation was performed with anisotropy along the centerline. The centerline was drawn from the estuary polygon using ArcGIS and converted into a "route" (Polyline M) using the *Linear Referencing* toolbox. Then R and M coordinates were calculated to each point by the tool *Locate features along routes*, calculating distance to the route at the same time. Bathymetry points then were plotted using R instead of X, and M instead of Y coordinates (figure 4). Kriging with anisotropy in the centerline direction (figure 1) was performed using a spherical model (90 degrees, ranges 150 and 300 m). As the authors of that method showed, there was no quick, simple and correct method to transform the points (or the interpolated raster) from RM back to Cartesian coordinates using GIS. But it was even not necessary to do this for modelling. The only result needed for the MOHID model was a bathymetry value for each curvilinear grid cell. So, the grid centers and corners were also transformed into channel-oriented RM coordinates (as points).

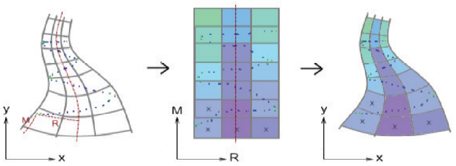

Figure 3. Transformation into channel-oriented coordinates.

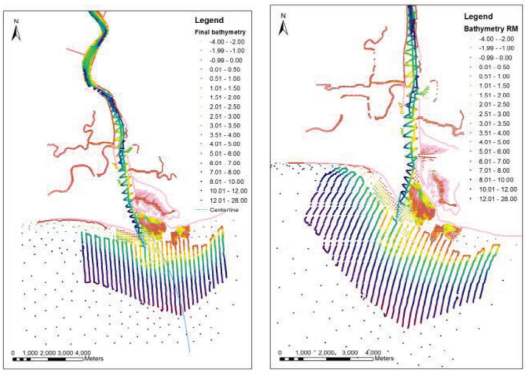

Figure 4. Bathymetry of the lower estuary: normal (left) and transformed to RM coordinates (right).

Voronoi diagram was selected as a representation of the curvilinear grid in RM space. The Voronoi polygons were created for the cell centers and clipped to the domain. Then the raster produced by kriging was overlapped by these polygons and average bathymetry value for each polygon was calculated from the overlaid raster cells by *Zonal Statistics* tool, in RM space. These average bathymetry values were attached to the curvilinear grid centers and then these centers were plotted again using their original X and Y coordinates (stored in the attribute table). Thus, a very simple and spatially correct back-transformation from RM space to XY space was performed (figure 5).

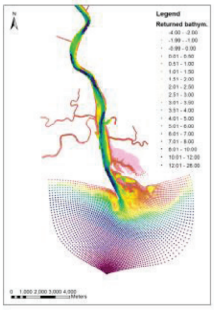

Figure 5. Back-transformed grid centers with the mean values.

The resulting surface (gridded bathymetry) was significantly different from the other interpolations. The holes and hills between the ship tracks almost disappeared and the deep thalweg was preserved everywhere (figure 6). This method produced the most realistic interpolation at the gaps in bathymetry data restoring the thalweg and the near-shore shallowing (figure 7).

4. HYDRODYNAMIC MODEL

Several periods with different river flow conditions were selected for simulation. The hydrodynamic model was a 2D model, forced by tidal water elevations at the open boundary and by the river discharge at the end of the estuary and tributaries. The daily flow values from SNIRH database were used. The MOHID code was used as compiled on the 11.04.2011 by Maretec.

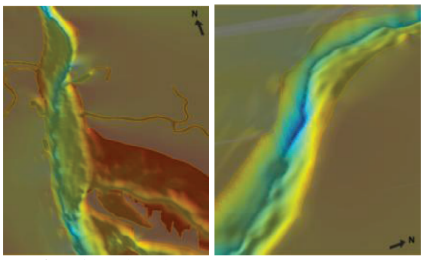

Figure 6. Surface based on kriging respecting varying anisotropy.

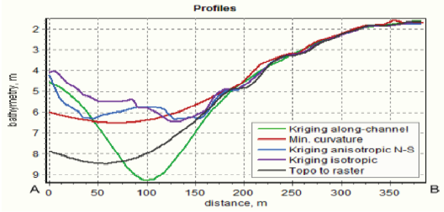

Figure 7. Comparison of a cross-section interpolations (the middle estuary).

In order to calibrate and validate the model, the results were compared to the measurements in several points along the estuary. The several input bathymetries based on the different processing methods in GIS were used for the simulations and then their results were compared. The calibration data included velocity components (N,E) integrated for the whole water column and water level data obtained from the Simpatico system (Garel *et al.*, 2011) located in the lower estuary. Also water height and along-channel velocities at the point near Ayamonte were used. The initial model was based on the grid data interpolated by MOHID's triangulation method. Then the several input bathymetries for the model were created, based on the different processing methods using GIS. They were compared to that reference model. The main test bathymetries for interpolation comparison were produced by Topo to Raster (ANUDEM) and kriging in RM coordinates methods. These changes of bathymetry almost did not change the resulting water lever but significantly changed velocities, comparing to the measurements at the Simpatico station. The results showed that by applying the advanced interpolation methods the results were improved (figure 8).

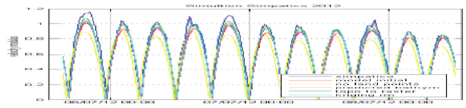

Figure 8. Comparing the models with different inputs at Simpatico station (velocity modulus).

And, the bathymetry interpolation in the channel-oriented coordinates significantly improved the direction of the current, which is visible in the change of the East velocity component (figure 9). The RMSE was calculated for each scenario, and it showed that the last model with bathymetry interpolated after river straightening produced in general the best result (figure 10).

5. DISCUSSION AND CONCLUSION

The computed velocities were in good agreement with the observations under well-mixed conditions with low river flow. However, they were slightly lower than the measured, and under stratified conditions the tidal asymmetry produced by the 2D model was wrong comparing to the measurements. Also, there was only one calibration point with good dense recent data (Simpatico).

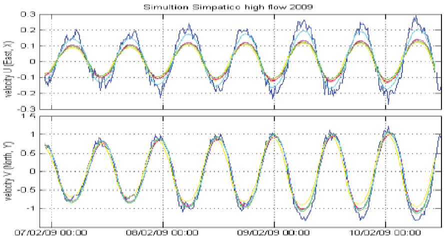

Figure 9. Comparing the models with different inputs at Simpatico station (velocity components).

The use of advanced interpolation methods improved the results (figures 8, 9). Because the current velocity in the shallow water depends on the water depth, the precisely described bottom due to correct interpolation is critical for the model. All isotropic interpolations produced artefacts on the resulting surfaces and then wrong velocity fields at these places (figure 11). The correct interpolation result was achieved only after transforming bathymetry points into flow-oriented coordinates and performing the interpolation with anisotropy along the centerline for this "straightened" estuary.

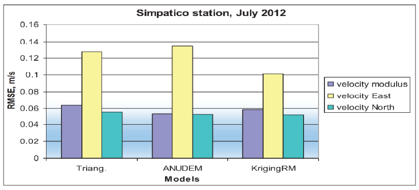

Figure 10. RMSE of the models with different inputs at Simpatico station.

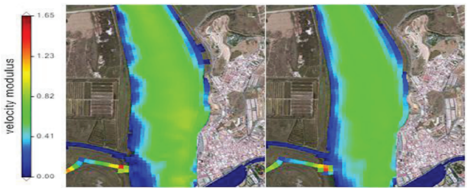

Figure 11. Velocity fields using bathymetry from Topo to Raster isotropic interpolation (left) and along-channel kriging (right).

Using the channel-oriented interpolation in the model significantly improved the direction of the water current and produced correct velocity fields (figures 10, 11). The RMSE of simulated velocities showed that the model using bathymetry interpolated in the flow-oriented coordinates produced in general the best result. So, good quality of the spatial input data proved to be critical for model accuracy. Validation of the model with different scenarios showed that advanced GIS tools are essentially needed for preparing accurate spatial inputs for coastal hydrodynamic models, improving the model results.

Acknowledgements

The authors would like to thank Erwan Garel (CIMA, University of the Algarve) and Juan Morales (University of Huelva) for providing the data for this study.

REFERENCES

Basos N., Martins F. and Rodrigues J. I. (2012). Using MOHID GIS to aid hydrodynamic modeling in the Guadiana Estuary. *5as Jorn. de Soft. Aberto para S.I.G. – SASIG 5*. November 15-17, Faro, Portugal.

Basos, N. (2013). *GIS as a tool to aid pre- and post-processing of hydrodynamic models. Application to the Guadiana Estuary.* Master thesis in Geomatics, Universidade do Algarve, Portugal.

Braunschweig, F., Leitao, P.C., Fernandes, L., Pina, P., and Neves, R. (2004). The object-oriented design of the integrated water modelling system MOHID. *Dev.elopments in Water Science*, 55, (2), 1079-1090.

Daniell, J.J. (2008). Development of a bathymetric grid for the Gulf of Papua and adjacent areas: A note describing its development. *J.Geoph.Res.,* 113(F01S15)

Garel, E., Ferreira Ó. (2011). Monitoring estuaries using non-permanent stations: practical aspects and data examples. *Ocean Dynamics*, 61, 891-902.

Garel, E., Pinto, L., Santos, A., and Ferreira, Ó. (2009). Tidal and river discharge forcing upon water and sediment circulation at a rock-bound estuary (Guadiana Estuary, Portugal).*Est..Coastal and Shelf Sc.*,84(2): 269-281.

Green, D., and King. S. (2003). Chapter 21. Progress in Geographical information systems and coastal modeling: an overview. In: Lakhan, V.C. (ed.). *Adv. in Coastal Modeling*, 67, 553-580.

Martins, F., Leitão, P.C., Silva, A., and Neves, R. (2001). 3D modelling of the Sado Estuary using a new generic vertical discretization approach. *Oceano.Acta*, 24:51-62.

Medved, I., Pribicevic, B., Medak, D., and Kuzmanic, I. (2010). Comparison of interpolation methods of bathymetry data used for monitoring of lake volume change. (In Croatian). *Geodetski list*, 64(87) (2), 71-86.

Merwade V.M., Maidment, D.R., and Hodges, B.R. (2005). Geospatial representation of river channels. *Journal of Hydrologic Engineering*, 10 (3), 243-251.

Merwade, V., Cook, A., and Coonrod, J. (2008). GIS techniques for creating river terrain models for hydrodynamic modeling and flood inundation mapping. *Environmental Modelling and Software*, 23, 1300-1311.

Merwade, V.M., Maidment, D.R., and Goff, J.A. (2006). Anisotropic considerations while interpolating river channel bathymetry. *J.of Hydrology*, 331 (3-4), 731-741.

Naoum, S., Tsanis, I.K., and Fullarton, M. (2005). A GIS pre-processor for pollutant transport modelling. *Env. Mod. and Soft.*, 20 (1), 55-68.

Wadzuk, B., and Hodges, B.R. (2001). Model bathymetry for sinuous, dendritic reservoirs. *The 6th International Workshop on Phy. Proc. in Natural Waters*, University of Girona, Catalonia, Spain, June 2001.