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Original research

Utilizing The HEC-RAS Sediment Model in Prediction of the Optimal Navigation Path for The Nile River Reach Downstream Esna Barrages

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Abstract

A one-dimensional numerical model (HEC-RAS) was calibrated to simulate morphological changes in the study reach of the Nile River downstream of Esna barrages by using the available field data of the years 2010 and 2013. The presented research utilizes the synergies between GIS and HEC-RAS in studying the morphological changes in the study area that affects directly the navigation condition and Proposes the optimum navigation path in the selected study reach based on the numerical model results data. Using data measurements, the model was calibrated and verified. It gave a reasonable agreement between the calculated and measured values for the water level and the morphological changes in the selected cross-sections and along the River's thalweg with accuracy 99.63% and 96.66% for hydraulic and sediment calibration and verification. It can be concluded from several runs of the model that the best equation for predicting morphological changes within the study area is the Ackers-White equation. Finally, the results indicate that the HEC-RAS model presents a satisfying performance for sediment transport.

Keywords: Nile River, Morphology, Navigation path, HEC-RAS, Ackers-White

1- INTRODUCTION

The Nile River is the main supply of freshwater in Egypt, also used in many fields such as transportation and tourism. Improving navigation in the course of the Nile River is essential for safe and economical transportation, and helping to increase the economic activities such as tourism and transportation of raw materials and goods. The study of navigation in natural rivers depends mainly on the assessment of changes in bed morphology(Elsayed, et al. 2019). Therefore, It is important to study morphological changes in the Nile Riverbed to determine the optimal navigation path and avoid releasing extra water for navigation in the periods of low discharges and thus secure water for vital demands(Sadek and Raslan 2019). Many studies of the Nile river morphology were carried out based on field investigations and numerical models (Nassar 2011, Sattar 2016, Sallam and Aziz 2003, Raslan 2009 and Raslan and Salama 2015). The idea of this study is to assess the morphological changes downstream Esna Barrages by applying hydraulic modelling tools (HEC-RAS and HEC-GeoRAS) and GIS software to delineate the navigation path depending on the predicted results.

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HEC-RAS (Hydraulic Engineering Center's – River Analysis System) a well-known software developed by the Hydrologic Engineering Center of U.S. Army Corps of Engineer is a free advanced system to analyze open channels (Brunner 2016). also the integration of HEC-RAS with GIS using HEC-GeoRAS Extension allows engineers to develop geometric data for easy import in HEC-RAS and view export water surface profile result data(Roshun et al. 2012).

2. STUDY AREA AND DATA COLLECTION

Data needed to simulate the study area and calibrate the model include the following:

2.1 Available Field Bathymetric (Geometric) Data

A hydrographic survey carried out in 2010 and 2013 by the Nile Research Institute (NRI) was used to simulate the study area bathymetric maps and covered about 11 km of the study reach from 168.5 km to 180 km (km from downstream Old Aswan High Dam) Fig. 1. These data were in form of coordinates vector points (x, y, z) along the entire study area and georeferenced using the world reference system (WGS-84 datum) to UTM zone, 36 North projection.

Fig. 1: study area

2.2 Hydrologic and Hydraulic Data

In order to simulate hydrologic characteristics of the reach under study, daily monitoring discharge releases through the Esna Barrages and corresponding daily water levels, as well as at different measurement points, are important. These data were provided by NRI; Fig. 2 illustrates daily discharge rates of 6-year recorded at Esna Barrages.

2.3 Available Sediment Data

The bed sample data available for the study area was used to define the bed gradation for each cross-section. Bed sample materials were mainly sand formation, about 18.87% coarse sand, 67.48% medium sand, and 7.70% fine sand with an average D50 of 0.38mm. All these data were obtained by RTA and NRI.

2.4 Model Description

HEC-RAS a well-known software developed by Hydraulic Engineering Center's – River Analysis System of U.S. Army Corps of Engineers is a free advanced system to analyze open channels. This model can perform Steady Flow Water Surface Profile computations, Unsteady Flow Simulation, Water Quality Analysis, and several hydraulic design features. HEC-RAS can also perform Sediment Transport Computations and geometrical changes of cross-sections with quasi-unsteady flow series data. A water surface profile is calculated for each flow in the time series. Also calculated Hydraulic parameters that needed for sediment processes. The model estimates sediment transport capacity using a variety of available methodologies. The sediment continuity equation is then solved in conjunction with sorting and armoring algorithms to estimate the actual volume of deposition or erosion. In addition, the functions of temporal entrainment and deposition (Brunner and Gibson 2005).

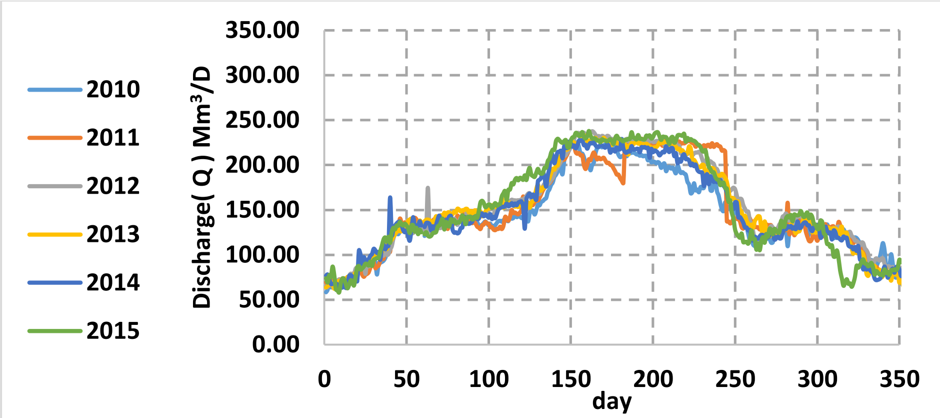

Fig. 2: The Hydrograph which flow through Esna Barrages from years 2010 to 2015

2.5 HEC-RAS One-Dimensional Unsteady Modelling

HEC-RAS solves the full, dynamic, 1-D Saint Venant Equation with an implicit and finite difference method for unsteady flow. In the late 1800s, Barre de Saint-Venant developed the Saint-Venant equations, also called the shallow water equations. The Saint-Venant equations were created from Mass Conservation (Equation 1) and Momentum Conservation (Equation 2) applied to a small control volume of fluid(Brunner , 2016).

Equations should be numbered in the usual way as in Equation (1),

continuity equation $$\frac{\partial A_T}{\partial t} + \frac{\partial Q}{\partial x} - q_l = 0 \quad (1)$$

momentum equations $$\frac{\partial Q}{\partial t} + \frac{\partial Q_V}{\partial x} + gA\left(\frac{\partial Z}{\partial x} + S_f\right) = 0 \quad (2)$$

Where:

A = Area of cross-sectional flow
Q = Discharge
ql = Lateral inflow perunite length
V = Velocity
$\frac{\partial Z}{\partial x} = Water\ surface\ slope$
S_f = Friction slope

2.6 HEC-RAS Sediment Transport Modelling

The sediment routing of HEC-RAS depends on solving the sediment continuity equation also known as Exner equation over reach control volume. (Equation 3) (Brunner 2016, Paola and Voller 2005):

Exner equation $$(1 - \lambda p)B\frac{\partial \eta}{\partial t} = -\frac{\partial q}{\partial x} \quad (3)$$

Where:

η = Bed elevation
B = Channel width
λp = Bed porosity

q = Transport sediment load

3. METHODOLOGY

The procedure followed to simulate the flow and sediment modeling using GIS and HEC-RAS model is illustrated step-by-step in Fig. 3.

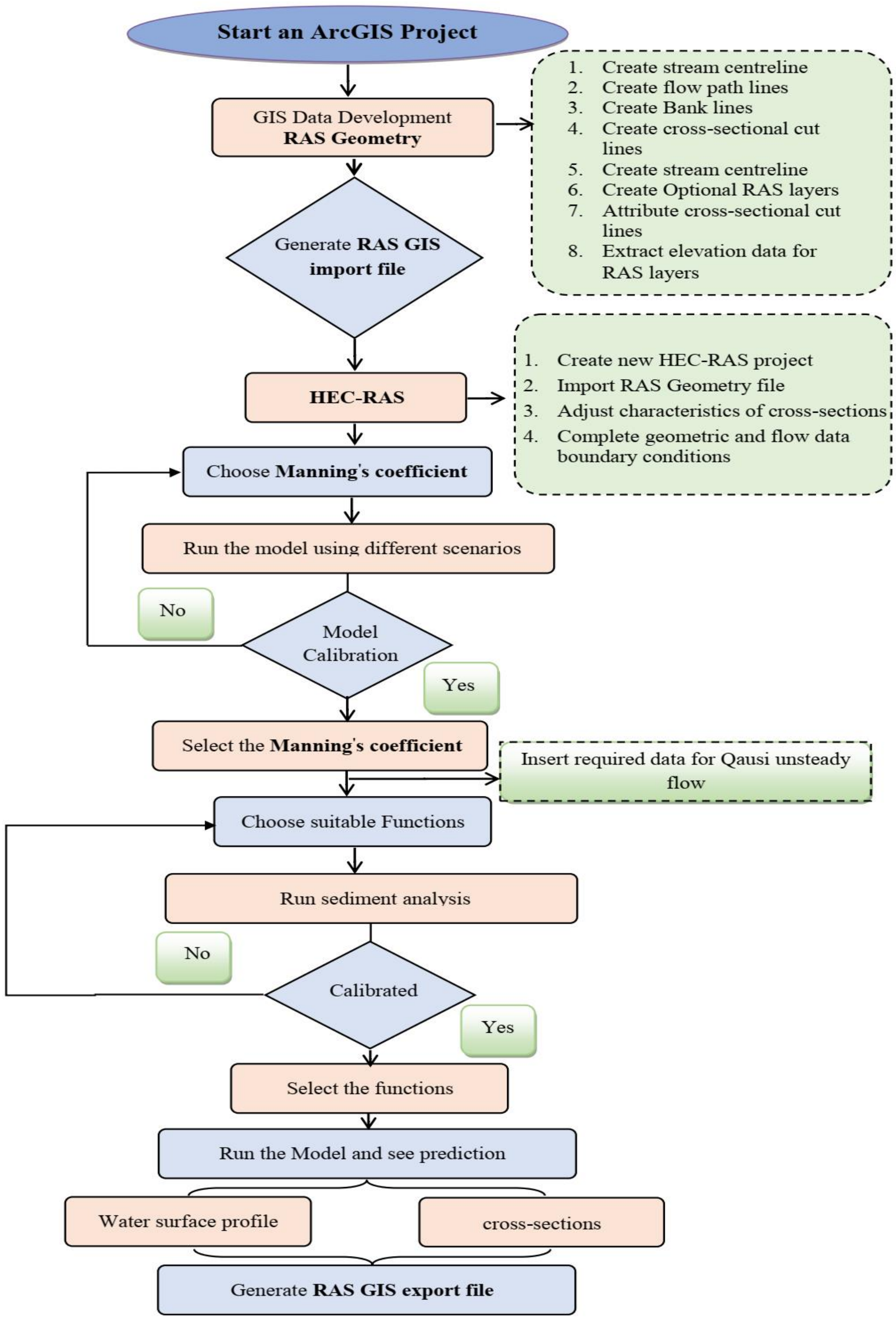

Fig. 3: Flowchart of the HEC-RAS algorithm

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3.1 Generation the Digital Terrain Models

These maps were created by Using the Radial Basis Function (RBF) interpolation method with the best performance by using ArcGIS software(Elsahabi and Negm 2017) for the bed topography from the bathymetric maps made in years 2010 and 2013 (available from RTA) with RMSE 0.206 m and 0.31 respectively, presented in Fig. 4.

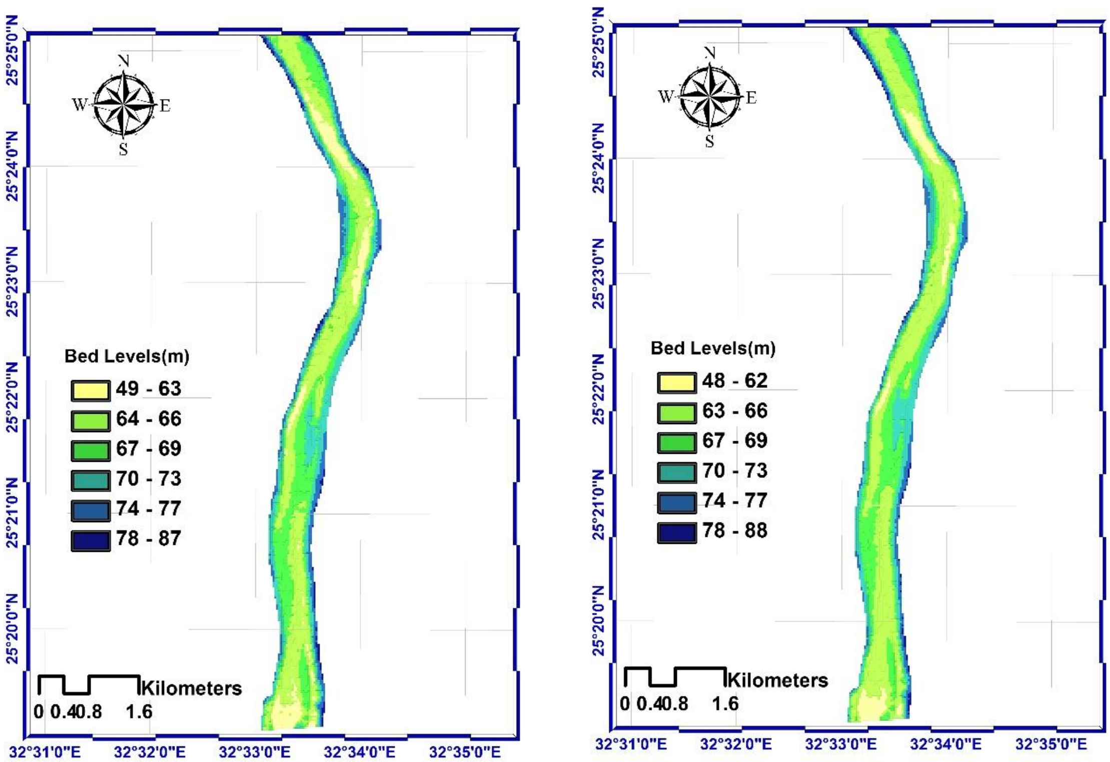

Fig. 4: Digital terrain model of the study reach for the year 2010 and 2013

3.2 HEC-GEORAS

The geometric data file will be prepared and establish the required layers by using the HEC-GEORAS tool which was installed in ArcMap in order to export to the HEC-RAS model, show Fig. 5.

3.3 Import RAS Geometry Data

A general schematic map was generated for the river reach including the introduction of virtual upstream and downstream points along with actual coordinates of these points and complete adjusting characteristics for each cross-section and in addition to the hydraulic parameters, see Fig. 5 and Fig. 6.

3.4 Boundary Conditions

For the upstream boundary conditions, a flow hydrograph of Esna Barrages for 6-years was used, and the downstream boundary conditions, a rating curve of discharge versus water stage for a km180 was set as shown in Fig. 7.

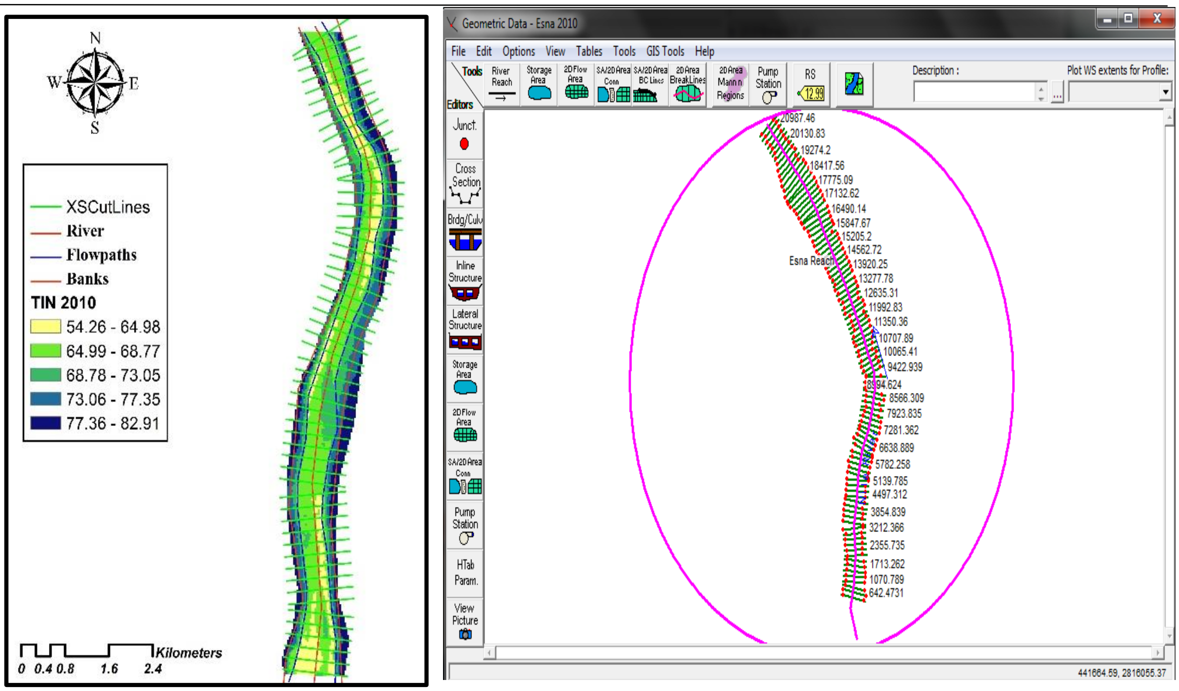

Fig. 5: Established layers in ARCMAP for HEC-RAS modelling and The geometric file after importing to HEC-RAS

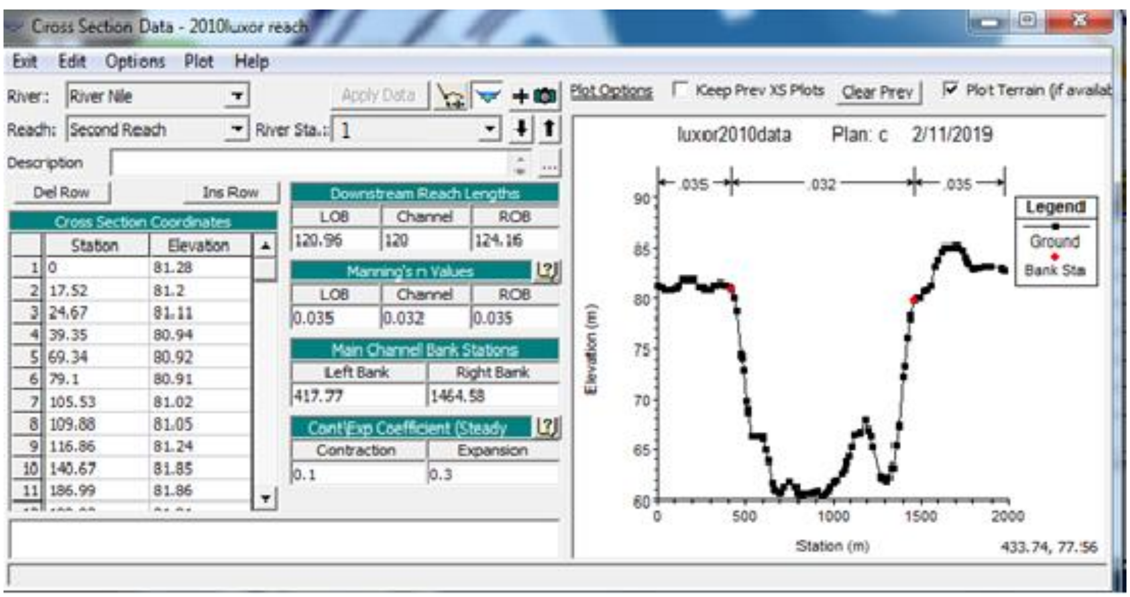

Fig. 6: Cross-sectional data of the reach

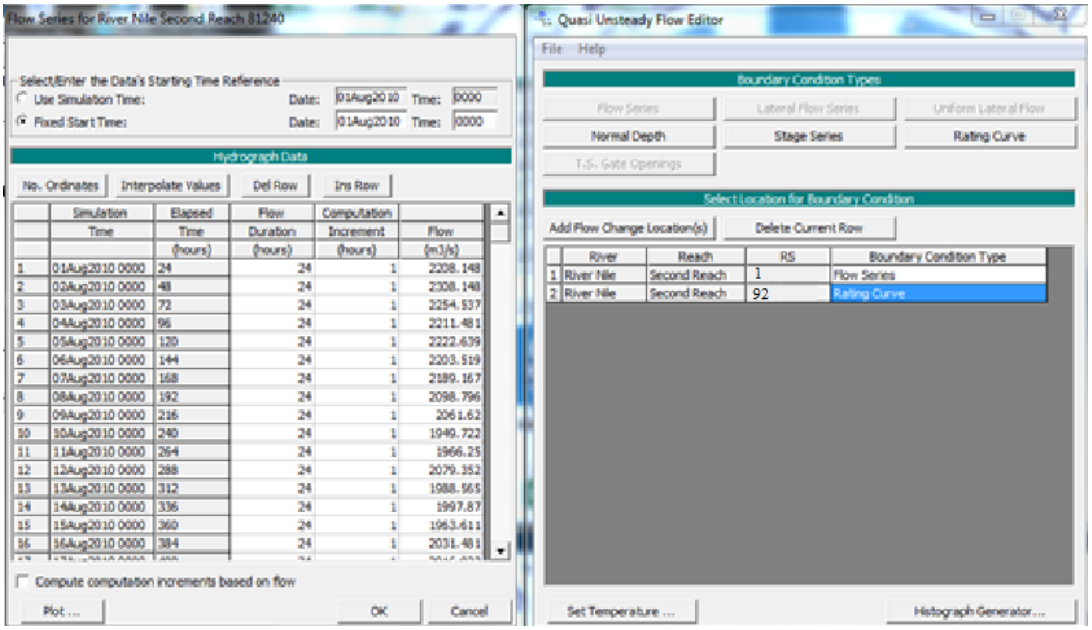

Fig. 7: HEC-RAS software's view of downstream and upstream boundary conditions

3.5 Sediment Boundary Condition

The model requests a second upstream boundary conditions in the form of a sediment transport boundary conditions, Grain sizes distribution and bed materials samples are important input factors for HEC-RAS as shown in Fig. 8.

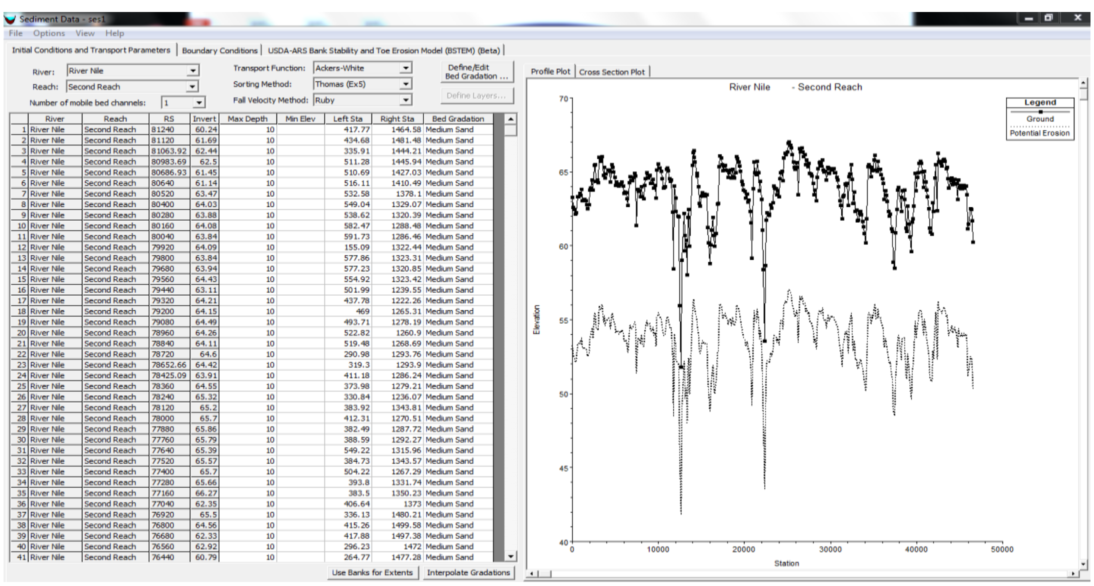

Fig. 8: A view of Sediment Data Software Menu

3.6 Model Accuracy

In order to evaluate the performance of the model in predicting future's bed levels changes, it is important to check the accuracy of the applied HEC-RAS model by adjusting the model inputs to match model outputs with field observation data for the selected period. The Literature review found that the correct determination of erosion and sedimentation in a river cross-section depends on the selection of the Manning roughness coefficient and the sediment transport equation. So, the model was calibrated at to stage:

3.6.1 Hydraulic model calibration

The calibration of the model was done based on real measurements of discharge and water levels. The model is calibrated hydro-dynamically by tuning hydraulic roughness value along the modeled study reach until the obtained water surface levels from the model match with those measured at observation stations. During model calibration, different roughness values were tested and the model was run repetitively. The results revealed a great agreement between the two water levels when taking the Manning coefficient 0.035 and 0.032 for the banks and channel respectively.

3.6.2 Sediment model calibration

HEC-RAS software can model the flow containing sediment load through seven sediment transport equations and four methods of calculating the fall velocity. Thus, 28 different combinations should be examined. Each of these sediment transport equations was compared with the natural conditions, and finally, the equations that had most overlapping with the natural conditions of the area were chosen as the best depositional equation. it was noticed that the Ackers-White equation and Ruby fall velocity method produced better results

4. RESULTS AND DISCUSSION

4.1 Calibration and Verification Results

A scatter diagram shown in Fig. 9 was established depending on the water levels along the study area for different discharges, to statistically measure the ability of the hydraulic model as a prediction tool. An acceptable agreement can be noticed. Accordingly, it can be concluded that the applied model is a useful tool for the simulation of water levels. Figures 10 and 11 showed the flow calibration and verification of the model in the case of minimum and maximum water levels through the longitudinal section of study reach, respectively. It can be seen that there is an acceptable agreement between the results from the model and the field measurements.

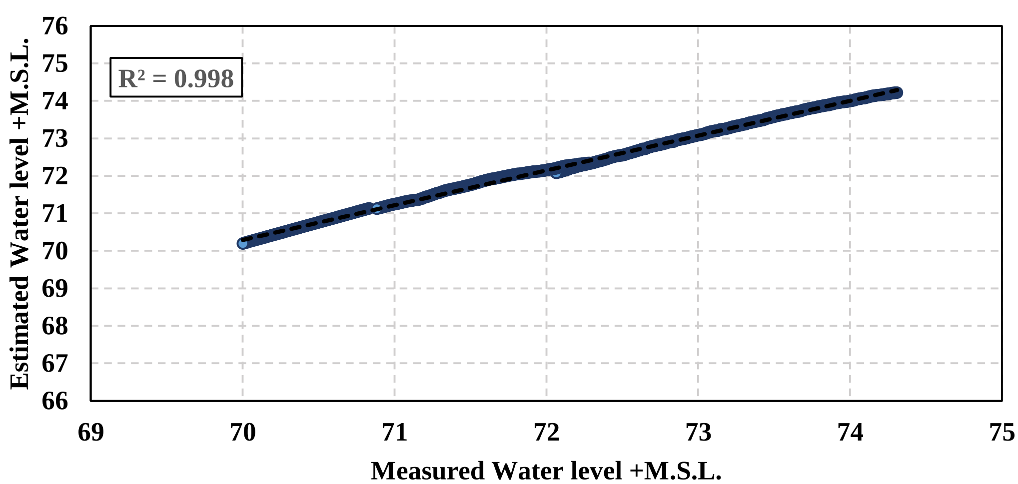

Fig. 9: A comparison of the water levels measured and predicted

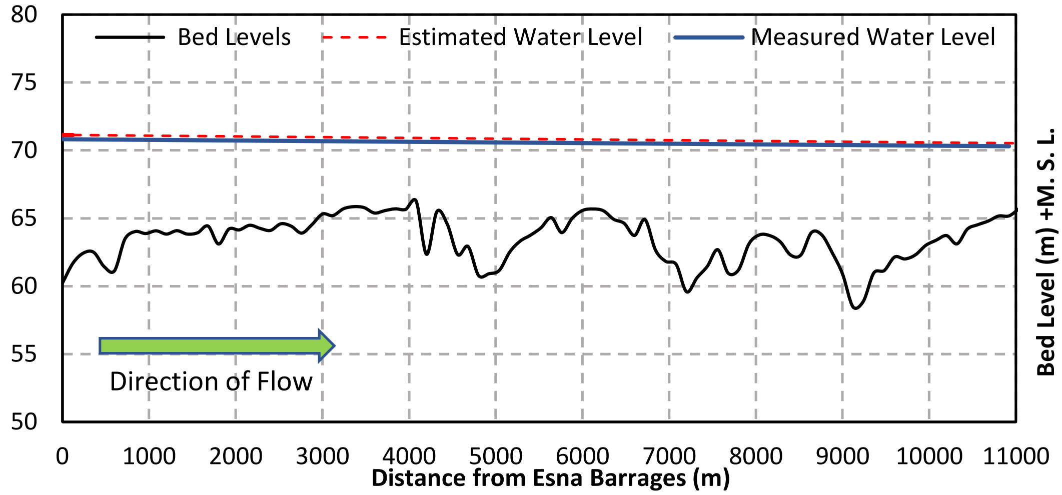

Fig. 10: Comparison between modelled and measured water levels through the longitudinal section in the study area deepest points (calibration at Min. WL)

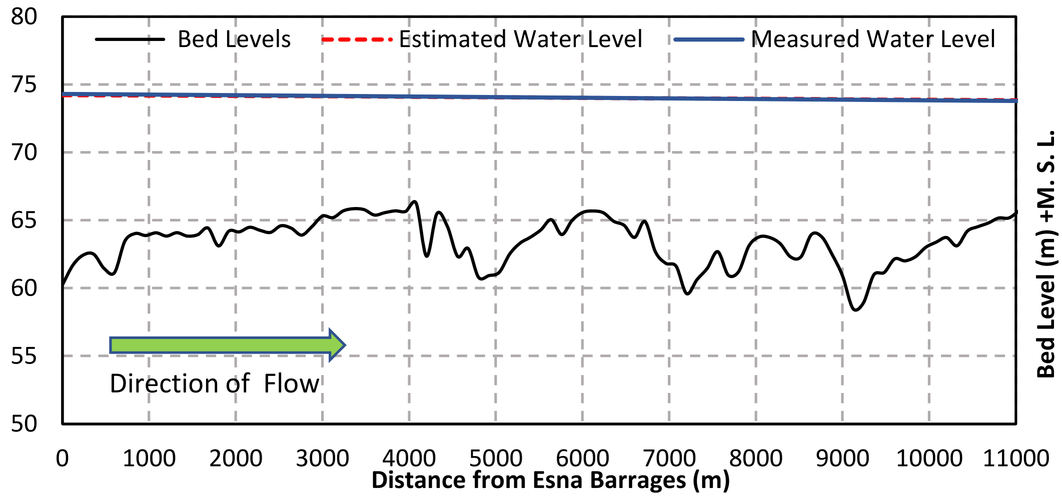

Fig. 11: Comparison between modeled and measured water levels through the longitudinal section in the study area deepest points (calibration at Max. WL)

The sediment calibration and verification process of the applied model can be achieved by the comparison between modeled and measured bed levels in the study area at the end of the year 2013. It is found from calibration runs that among sediment transport and fall velocity equations, the best sediment transport equation that gave the best predictions and can be used to predict the morphological changes within the study area is the Ackers-White equation and Ruby fall velocity method. Statistical analysis was performed via establishing a scatter diagram as shown in Fig. 12 depending on the bed level points of the study area, the scatter diagram was established to compare the observed bed levels and the predicted ones, an acceptable agreement was noticed between the measured and predicted bed levels (R^2 = 0.966). Fig. 13 shows the locations of the cross-sections that used for the calibration and verification of the sediment model as are shown in Fig. 14 and Fig. 15. Finally, it can be concluded that the HEC-RAC simulation model is well verified and provides reasonable stability to predict the future bed levels along the Nile River.

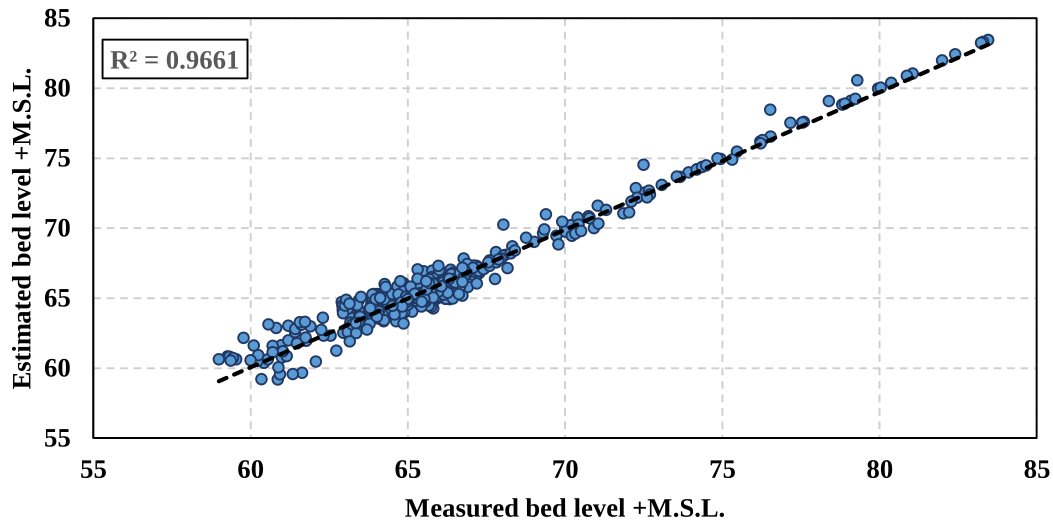

Fig. 12: Comparison between modelled and measured bed levels at the end of year 2013

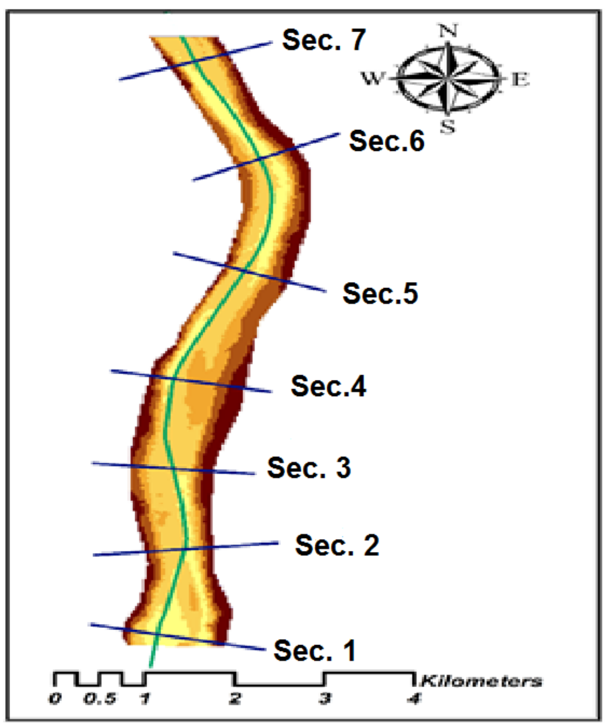

Fig. 13: Location of the cross-sections for HEC-RAS model verification

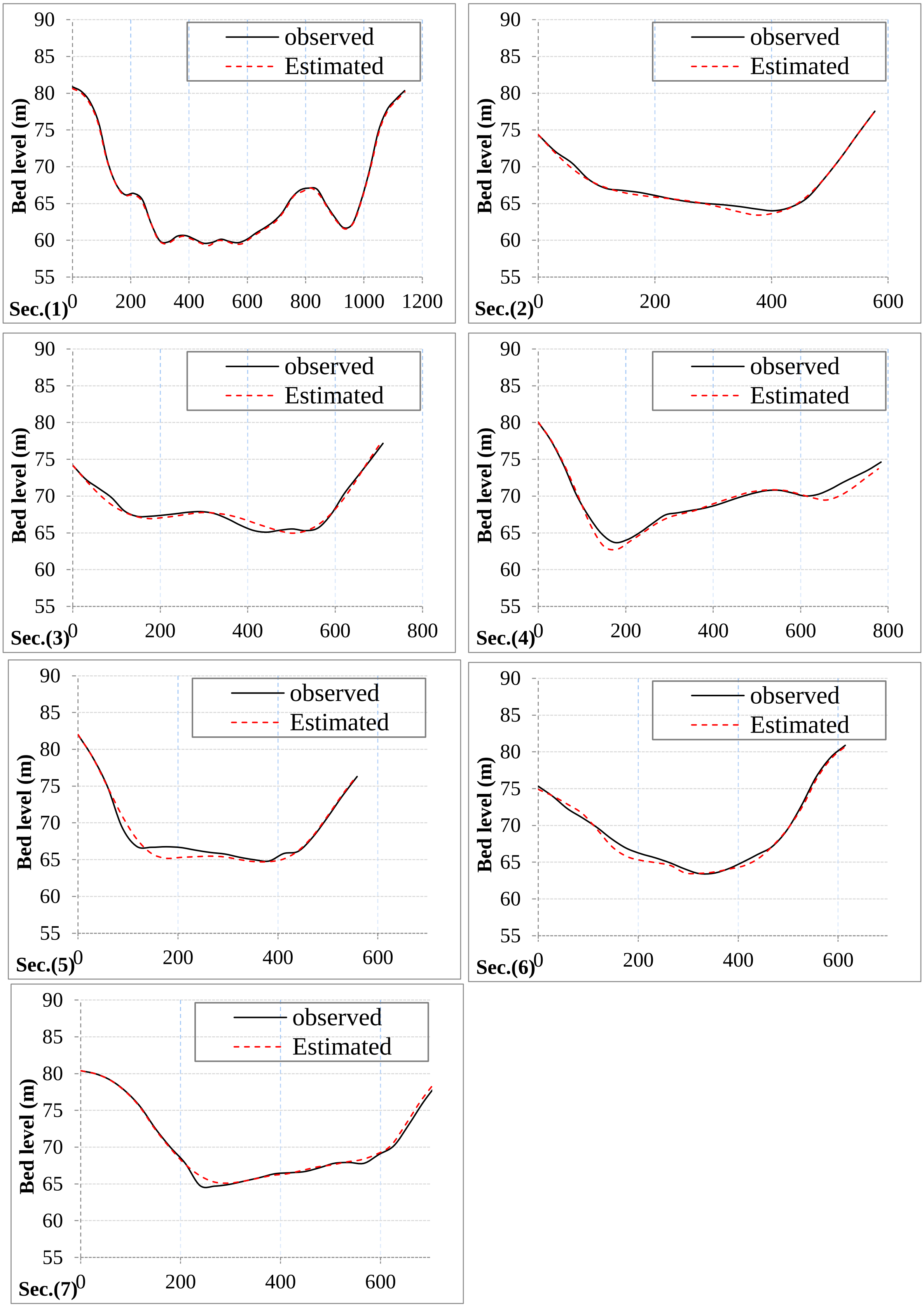

Fig. 14: Flow sediment transport calibration using Ackers-White equation

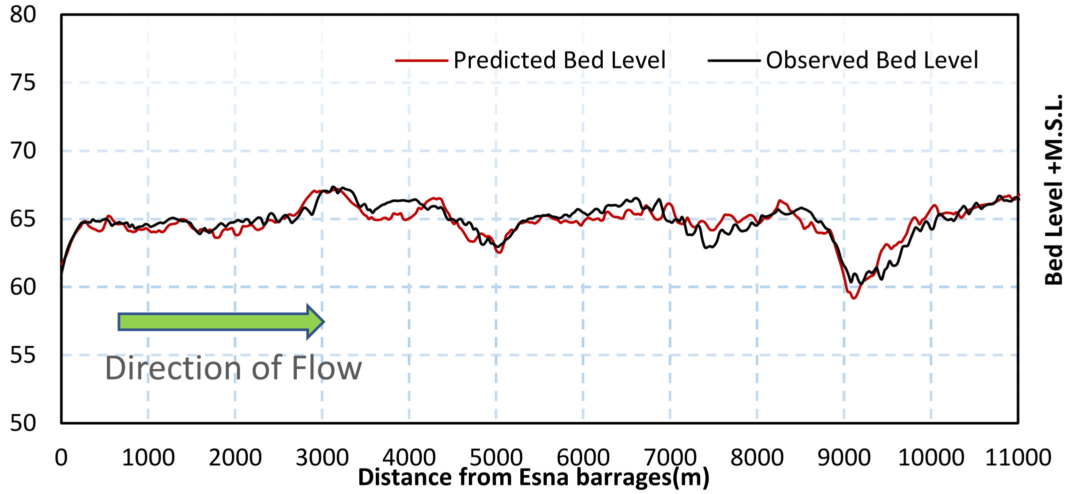

Fig. 15: Comparison between modelled and observed (measured) bed levels area through the longitudinal section of the study area deepest points in the year 2013

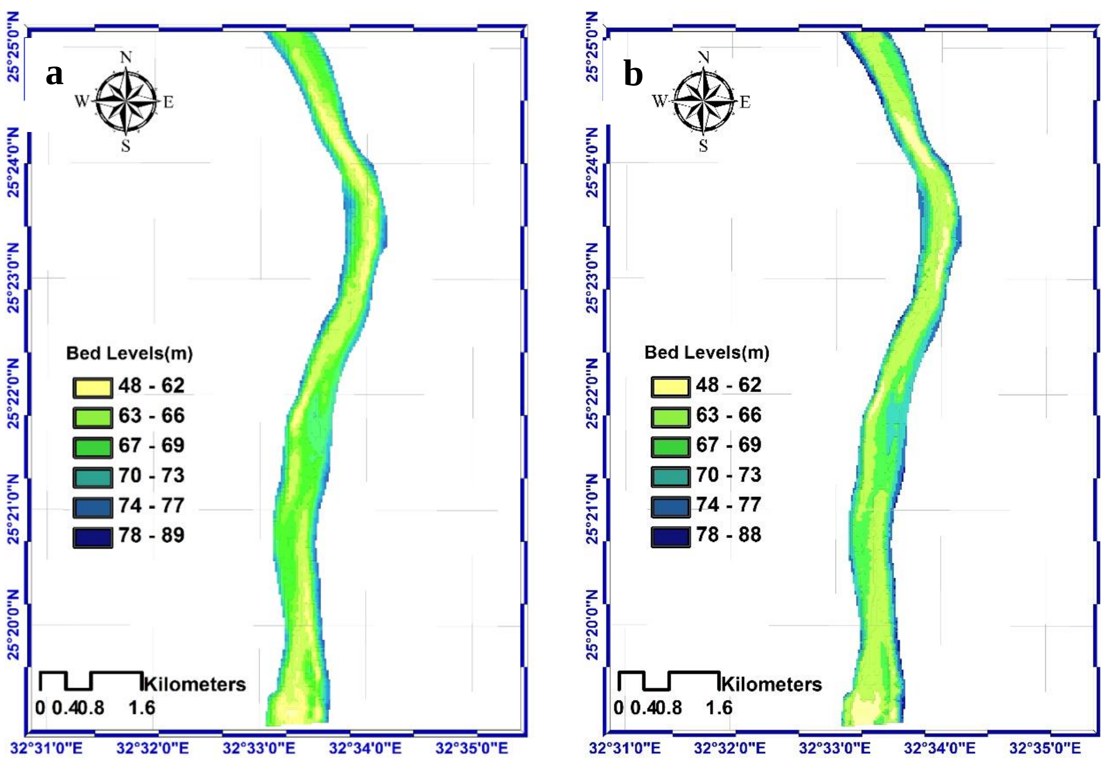

Fig. 16: The digital terrain models of the study area for the year 2013 that was created from (a)observed data and (b) predictive cross-sections of HEC-RAS

4.2 Predicted Bed Levels Data

After the calibration process, the model was run until the year 2030 to predict bed surface map for this year and evaluate the predicted sediment and erosion amounts within the study area until the year 2030 by their statistical analysis using ArcGIS software. The exported results from the sediment transport simulation gave a prediction of the overall sedimentation process occurring along the study area (see Figure 17 and Figure 18).

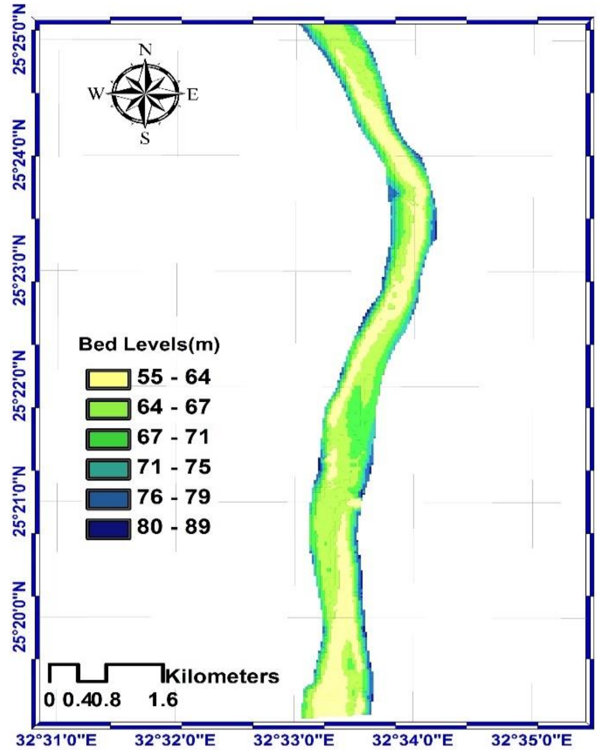

Fig. 17: The predicted bed maps of the study reach for year 2030

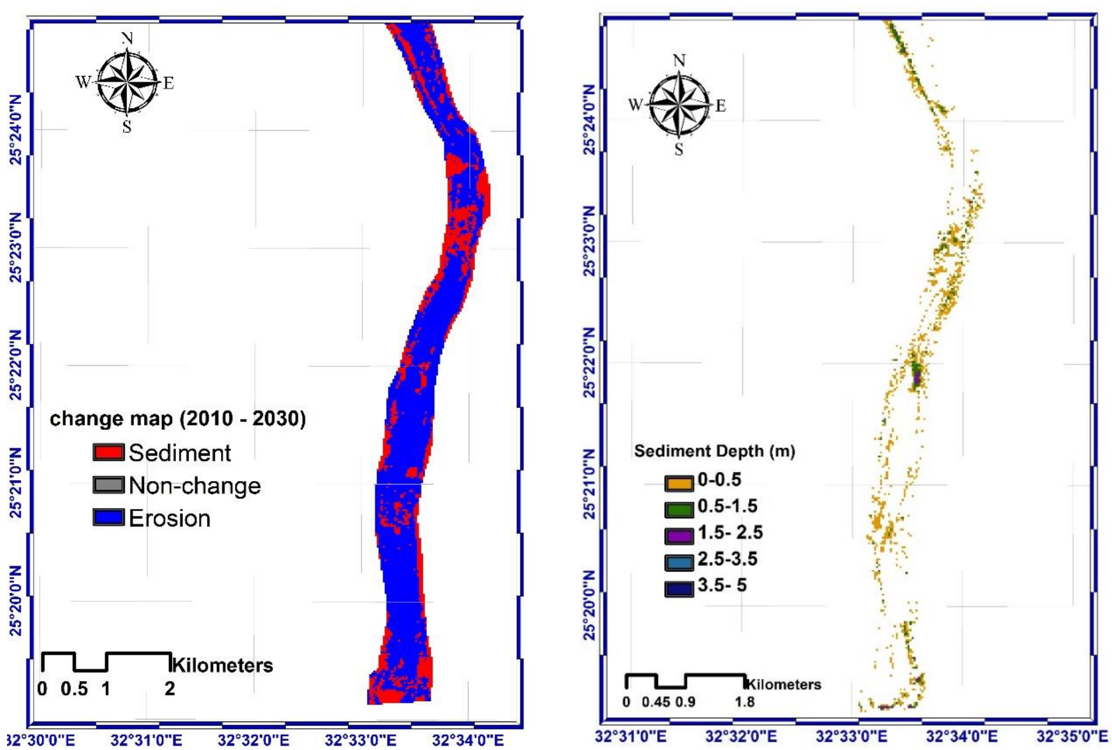

Fig. 18: The map of changes between the bed levels in 2010 and 2030 and the map of expected sediment depth

Table 1: Quantitative analysis of the predicted sediment and erosion amounts in the period (2010 to 2030)

Time period	Amount of sediment (m^3)	Amount of erosion (m^3)
2010-2030	3168900.00	6839100.49

Finally, the navigation path is designed to be in the deepest part of the reach that it is easy to observe by using the created digital terrain model. The navigational path was plotted by taking into account the standards of safe navigation within this study area (width of 100 m and effective depth more than 2.3m) as shown in Figure 19, A longitudinal section was taken through the predicted longitudinal path (Figure 20). from analyzed the results by subtracting the designed bed level of the navigation channel from the minimum water level during the period of minimum discharge release, it is clear that the delineated navigational path for this part will still be a safe area without any expected navigation bottlenecks, possibly due to the hydraulic action of Esna Barrages. Finally, some locations are very close to the bed level for the navigational path. So, it can be expected that their locations will be exposed to deposition in the near future which may be causing obstructions for navigation.

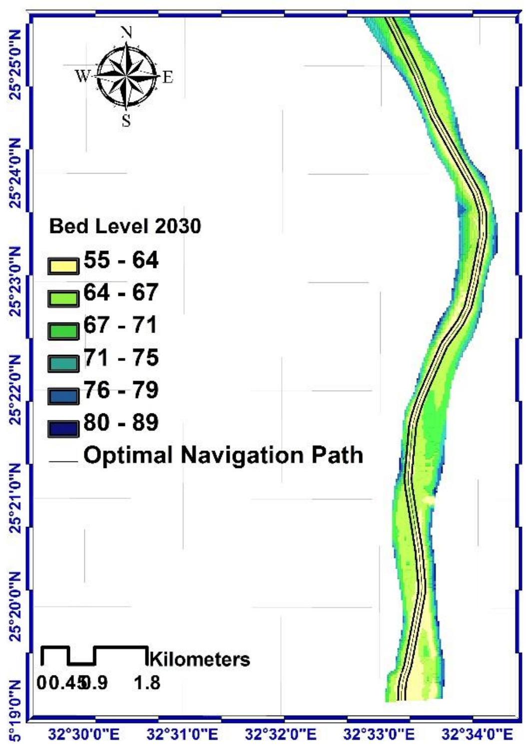

Fig. 19: The optimal navigation path of the year 2030

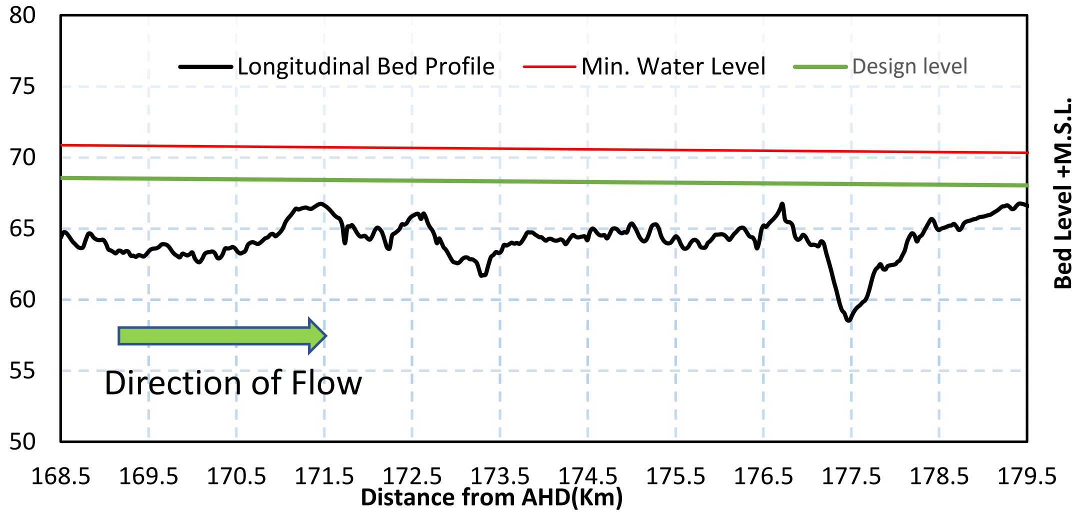

Fig. 20: The predicted longitudinal navigation path

5. Conclusions

This study has investigated the ability of the HEC-RAS numerical model to predict erosion and sediment transport where the model was used to simulate the study area from the Nile River near the city of Esna to predict the morphological changes along the study reach according to the discharges that the Esna Barrages launched over the last years. The model was calibrated and modified by trying and error first via adjusting the roughness coefficient that gives estimated water levels matched with those measured and found that the trial of 0.035 and 0.032 for banks and channels respectively represent the bed roughness of the study area was given to the model with accuracy 99.63%. The second was sediment calibration and verification, the model was calibrated by running several times and it is found from these calibrations runs that the most appropriate sediment transport equation for the study area that can be used to predict the morphological changes is the Ackers-White equation and the accuracy verification with measured bed level of the year 2013 was 96.66%. Accordingly, the model is reliable to give acceptable predictions. So, it was used to predict future riverbed morphological changes and evaluate the predicted sediment and erosion amounts within the study area until the year 2030 by their statistical analysis using ArcGIS software. Accordingly, the exported results from the sediment transport simulation were used in creating digital terrain model and delineate the optimal future prediction of the navigable path.

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