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Modeling the hydrodynamic interactions between the river morphology and navigation channel operations

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Abstract: The Nile River is the main route for inland navigation in Egypt. The vessels navigating through inland waterways generate complex physical forces that need to be studied extensively. Quantifying the effects of vessels sailing along a waterway is a complex problem because the river flow is unsteady and the river bathymetry is irregular. This paper aims to investigate the hydrodynamic effects resulting from the movement of vessels such as return currents around the vessel, the draw down of the water surface, under keel clearance, and the shear stress induced by vessels operating in the Nile River. Modeling such effects has been performed by applied the two-dimensional ADH (adaptive hydraulics) model to a river reach for different navigation channel operation scenarios. The obtained results show that the draw down heights, the water fluctuation, and the shear stress magnitude are larger when the river cross sectionals are narrow and the shallow water depths. These river sections are considered more disposed to bed erosion and it is morphologically unsafe. The section having the narrowest width and the lowest depth was associated with the largest drawdown percentages of 98.3% and 87.3% in one-way and two-way scenarios. While the section having the widest width and the largest depth was associated with the least drawdown percentages of 48.5% and 51.9% in one-way and two-way scenarios.

The section having the narrowest width and the lowest depth was associated with the largest fluctuations of 22.0 cm and 41.9 cm in one-way and two-way scenarios. While the section having the widest width and the largest depth was associated with the least fluctuations of 0.6 cm and 1.8 cm in one-way and two-way scenarios.

The section having the narrowest width and the lowest depth was the worst section for under keel clearance of 5.0 cm and 33.3 cm in one-way and two-way scenarios. While the section having the widest width and the largest depth was the best section, where its clearance values were 183.2 cm and 155.0 cm in one-way and two-way scenarios.

It is concluded that a numerical model is a valuable tool for predicting and quantifying the hydrodynamic effects of vessels moving through a two-dimensional flow field and can be used to evaluate different scenarios that are difficult to measure in the field or a physical model. Also, it provides visualization products that help us understand the complicated forces produced by vessels moving in a navigation channel.

Keywords: adaptive hydraulics (ADH) model, draw down, navigation channel, the Nile River, restricted waterway, return flow, shear stress

INTRODUCTION

The Nile River is the important inland transportation in Egypt with tremendous economic benefits. The navigation through the Nile River waterway is usually considered the most sustainable. The temporal alteration of the hydrodynamic regime in the river associated with the movement of navigation traffic has significant effects on riverine ecosystems and needs to quantify and be addressed fully in detail. The main types of configurations of waterways are open or unrestricted, restricted (bottom dredged), and canal. The Nile River is considered a restricted waterway. Navigation through canals and the restricted shallow waterways are affected by several parameters related to both the channel and the vessel. Vessels traveling in restricted waterways often generate waves that may have a significant impact on the bed and river banks. Both the primary (draw down) and secondary waves (divergent and transverse) can cause problems.

The waterway characteristics that affect navigation are channel dimensions (width and depth), bottom material characteristics, current velocity, wind speed, and direction [Samuel 2014]. Meanwhile, the parameters related to the target vessel are length (L), beam (B), maximum draft (d), speed (v_v), maneuverability, and traffic density. To facilitate the movement of vessel traffic in the Nile River, the navigation channel is maintained by River Transport Authority (RTA) and Nile Research Institute (NRI) at a minimum width of 100 m, and a minimum depth of at least 2.30 m [Elsayed *et al.* 2019].

The vessel movement through a waterway is associated with different hydrodynamic effects such as return flow, draw down, and fluctuation at surface water elevation [Das *et al.* 2012]. The interaction between a sailing vessel and the direct surrounding water can be divided, according to Schiereck [2004] into three main components: the primary wave, secondary wave, and propeller wash. As a vessel moves through a waterway, it produces a depression in the water surface and generates return currents around the vessel, this depression called (draw down) [Berger, Lee 2005].

The distance available under the vessel is known as under keel clearance. For the navigation to be considered safe, the "Net UKC" must always remain greater than a predetermined safety margin [Moustafa, Yehia 2017].

In restricted waterways, the water is restricted to a small area around the vessel due to the boundaries of the banks. Thus, the hydrodynamic effects are more critical in restricted waterways than in unrestricted ones. In restricted waterways, the boundaries of the banks restrict the water. In case the vessel moves in the same direction of the flow, it causes an increase in water volume transported in front of the vessel. Moreover, it results in an increase in the velocity of the water at the bow and stern of the vessel. But in case the vessel moves opposite to the flow direction, it results in a decrease in the velocity of the water at the bow and stern of the vessel [Althage 2010].

Secondary effects result when the primary effects encounter the river bed, riverbanks, or a change in channel morphology. The vessel's propeller jet affects the bed of the Nile River and causes turbidity and suspended sediments. The vessel-induced bed shear stresses are important because sediment suspension and transport are determined by the shear stress acting on the bed. For a sediment particle to be suspended and transported within the flow, the shear stress acting on the particle must be higher than a critical shear stress value. The shear stress-induced on the bed by a passing vessel is a large portion of the total bed shear stress, so calculating the vessel induced bed shear stress is important in determining sediment transport patterns [Hammack *et al.* 2008]. Švetak [2001], studied the effect of vessel passage at restricted waterway on under keel clearance. To avoid occurring erosion in the river bed, the volume of water pushed ahead of the vessel must return down the sides and under the keel of the vessel. The streamlines of return flow were speeded up under the vessel. This caused a drop in pressure resulting in the vessel dropping vertically in the water. The overall decrease in the under-keel clearance fore or aft of the vessel was called vessel squat. The squat was the decrease in under-keel clearance caused by this forward motion.

Maynord [2003] investigated the vessel effects in navigation channels, which could be broadly classified as short period and long period. Short period effects included waves formed at the bow and stern and, in some cases, short period waves that resulted from the draw down of the water level in shallow water for high-speed vessels. Long-period effects included draw down of the water level, return velocity, and surge of the water level above the ambient level. Pokrefke *et al.* [2003], estimated the effect of vessel-induced exchange for the upper Mississippi River. And Verheij [2006], investigated the hydraulic effects of vessel passage on the waterway channel and computed the shear stresses induced by the propeller jet of the vessel.

Racionero [2014], studied the effect of the vessel passage in the Gota Alv River. It was concluded that the vessel motion through a waterway generated a wave system formed by two different components; the primary component, and the secondary component.

The current study is using the adaptive hydraulics (ADH), model [Tate *et al.* 2008], applied an ADH model to simulate a vessel traveling upstream along the channel. The ADH simulation generates the velocity pattern around the vessel caused by the return current and into the surrounding shallows. Jong de *et al.* [2017], applied a numerical model (X-Beach) to evaluate the potential effects caused by passing vessels along with one of the main entrance channels of the Port of Rotterdam. A numerical model described ambient flow and wave conditions.

The main objective of this study is to investigate the hydrodynamic effects resulting from the movement of vessels in the navigation channel using a two-dimensional numerical model. The specific objectives of the study are:
- compute the draw down due to different vessel traffics scenarios;
- estimate the net clearance at the navigation channel;
- analysis of the water surface fluctuation that occurs as a result of vessel movement;
- determine the return velocity at the bow and stern of the vessel;
- evaluate bed shear stress at the river bed.

MATERIALS AND METHODS

STUDY AREA

The Nile River is divided into four reaches segregated by four barrages. The study area is located in the fourth reach, which extends from Assuit barrage at km 544.78 from High Aswan Dam

(HAD) to Delta Barrage at km 953.00. The study area is with a total length of 9.34 km. It was selected because of their distinct characteristics, which is geometrically complicated and characterized by the morphological changes and navigation bottlenecks. The study area is located in the river reaches with one or more islands and a large side channel. The river widths at the study area are ranged between 600–1400 m measured on the dominant water surface as seen in Figure 1.

For the study area; the bathymetric, hydrologic, and hydraulic data such as stage and flow hydrographs, water velocities, and rating curves were collected to establish the initial and boundary conditions of the model. The bathymetric data were obtained from the contour maps, produced from the recent hydrographic survey of the river bed for the year 2016 provided by the Nile Research Institute (NRI). The river channel geometry presented by Easting, Northing, and Elevation (E, N, and Z) points were used for the mesh generation. The coordinates of the mesh were referenced to the WGS84 ellipsoid (World Geodetic System, 1984) with Universal Transverse Mercator (UTM) Projection. The river bed levels were clarified with an accuracy of ±5 cm by using echosounder flow depth measurements. A hydrological study was carried to analyse the flow discharges and the corresponding water levels daily of the study reach. The river discharges from Assiut barrage was analysed as the upstream boundary condition. The study area is located between two water level gauge stations; the first is the El-Kraimat gauge station at km 87.90, and the second is the Beni Sweif gauge station at km 118.40, as seen in Table 1.

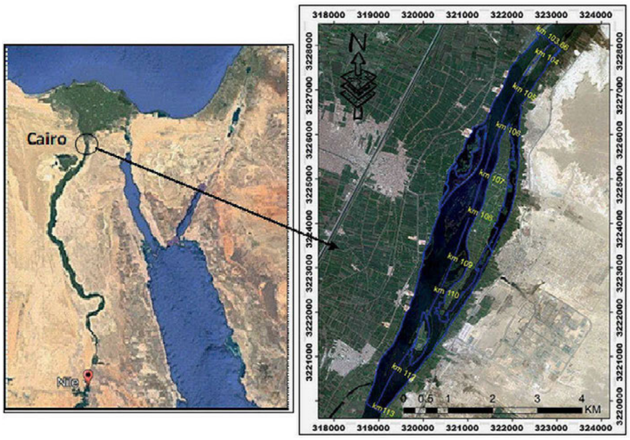

Fig. 1. Location of the study area; source: own elaboration

METHODOLOGICAL APPROACH

The vessel-induced wave analyses were performed to provide an evaluation of water level fluctuations and wave-induced current velocities generated within the study site by passing vessels. The two-dimensional numerical model was used to simulate water level fluctuations and return velocity generated by passing vessels within the river moving up bound and down bound in the vessel channel.

In this research, the main procedures are shown in the flow chart of in Figure 2 as follows:
- select the study area with total length (9.34 km) in the fourth reach;
- collect the required bathymetric, hydrological, and hydraulic data for this study area;
- apply the adaptive hydraulic model (ADH) to operate the navigation channel with a vessel and apply the different scenarios;
- investigation of the draw down due to vessel passage;
- estimating net clearance of the vessel;
- evaluating the fluctuation that occurs as a result of the passage of the vessel;
- calculating the velocity difference at the bow and stern of the vessel;
- evaluating bed shear stress due to vessel passage.

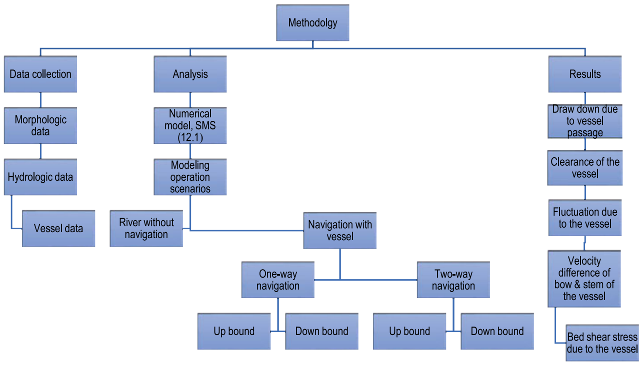

Fig. 2. The flow chart of the research methodology; source: own elaboration

Table 1. Data collection for the study area (2016)

Data	Location	Source	Usage
Bathymetry survey	river reach length of 9.34 km	Nile Research Institute	grid development
Discharge	downstream Assuit barrage	Nile Research Institute	downstream boundary condition (BC)
Water level	El-Kraimat and Bani Sweif gauges	Nile Research Institute	upstream boundary condition (BC)
Velocity measurement	three cross sections at km 105.96, 106.14, and 106.3	Nile Research Institute	calibration-verification
Bed samples	eight bed samples at km 105.96, km 106.14, and km 106.3	Nile Research Institute	roughness coefficient
Vessel characteristic	in the Nile River	River Transport Authority	navigation channel operation

Source: own elaboration.

NUMERICAL MODELING

MATHEMATICAL FORMULATION

The adaptive hydraulic model (ADH) is used to simulate the hydrodynamic effects of vessels moving through a waterway. The ADH is a computational fluid dynamics package that solves the Navier–Stokes equations and shallow-water depth-averaged Navier–Stokes equations on two dimensional. It was developed by the Coastal and Hydraulics Laboratory at the Engineer Research and Development Center in Vicksburg, 2007. It is using empirical relations developed by MAYNORD [2000], to calculate the bed shear stresses induced by a barge bow and towboat propeller, which can be used to predict sediment transport. This is accomplished by calculating a pressure field, which applies a draft equal to that of the modeled vessel. The different datasets being generated after running the ADH model in the water surface modeling system SMS13.0 software visualization tool. The model is based on several equations described as following:

$$\frac{\partial Q}{\partial t}+\frac{\partial F_x}{\partial x}+\frac{\partial F_y}{\partial y}+H=0 \tag{1}$$

$$Q=\begin{Bmatrix} h \\ uh \\ vh \end{Bmatrix} \tag{2}$$

$$Fx=\begin{Bmatrix} \text{uh} \\ u^2h+\frac{1}{2}gh^2-h\frac{\sigma xx}{\sigma} \\ uvh-h\frac{\sigma yx}{\sigma} \end{Bmatrix} \tag{3}$$

$$Fy=\begin{Bmatrix} vh \\ uvh-h\frac{\sigma yx}{\sigma} \\ v^2h+\frac{1}{2}gh^2-h\frac{\sigma yy}{\sigma} \end{Bmatrix} \tag{4}$$

$$H=\begin{Bmatrix} 0 \\ gh\frac{\partial zb}{\partial x}+n^2g\frac{u\sqrt{u^2+v^2}}{h^{1/3}} \\ gh\frac{\partial zb}{\partial y}+n^2g\frac{v\sqrt{u^2+v^2}}{h^{1/3}} \end{Bmatrix} \tag{5}$$

where: h is flow depth; u and v are velocities in x and y directions; g is gravitational acceleration; ρ is flow density; σxx, σyy, σxy and σyx are shear stresses in which the first subscript indicates the direction and the second indicates the face on which the stress acts because of turbulence; zb is the river bed elevation; n is Manning's friction coefficient, and vt is the kinematic eddy viscosity.

The Reynolds stresses are determined using the Boussinesq approach to the gradient in the mean currents:

$$\sigma xx=2\rho vt\frac{\partial u}{\partial x} \tag{6}$$

$$\sigma yy=2\rho vt\frac{\partial v}{\partial y} \tag{7}$$

$$\sigma xy=\sigma yx=2\rho vt\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right) \tag{8}$$

MESH GENERATION

The model has been used to generate the mesh which represents the study area by providing element and node information in the appropriate format. The mesh file defines the finite element, by assigning coordinates and elevations to nodes located at the Vertices of the elements. The element width in the navigation channel was 5 m in the lateral direction and 15 m in the longitudinal direction, but the element width out navigation channel was 25 m. The number of all elements was 78,289 and the number of all nodes was 39,375, as shown in Figure 3.

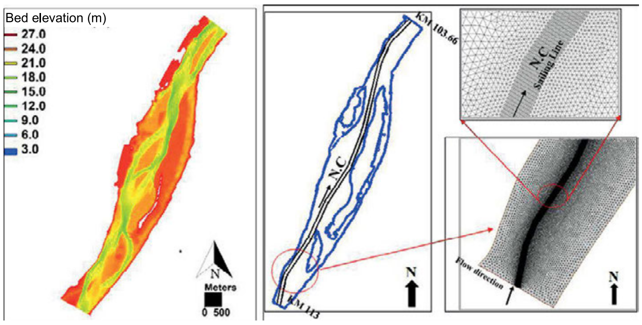

Fig. 3. Study reach mesh element composition; source: own elaboration

The vessel geometry must also be considered in areas along the sailing line for the coarse mesh.

The two-dimensional (2-D) mesh near the vessel is described in terms of lateral and longitudinal element sizes. Longitudinal means along a vessel's sailing line, and lateral means normal to a vessel's sailing line. After a convergence study was conducted, two elements completely within the vessel footprint were suggested for sufficient lateral refinement. This level of refinement should be used around any possible sailing line of each vessel being simulated. The number of elements that span the vessel length is related to the elements spanning the boat width by the element aspect ratio (AR) defined by:

$$AR=L_e/W_e \tag{9}$$

where: L_e is element length, W_e is element width.

The aspect ratio, the element length divided by the element width, of the elements within the vessel footprint should be about three or less [MOUSTAFA, YEHIA 2017]. The elements near the sailing line should be right triangles because the pressure-head contours from simulation show a vessel footprint reflective of the vessel shape.

MODEL CALIBRATION

The initial water levels and bed elevations were set as the initial boundary conditions in the model. The inflow of the Assiut Barrage was used as the upstream boundary condition. The water levels at Al-Korimat and Beni Suef gauge stations were used as the downstream boundary condition. In the calibration process, the numerical model was run for the minimum river flow of 47.50 mln $m^3 \cdot day^{-1}$ which was corresponded to the water level (21.75 m) at the downstream of the river reach. The model runs were performed by adjusting the roughness coefficient of 0.025

for the river bed in the modeled study area to achieve the best agreement between the measured and simulated values, as shown in Figure 4.

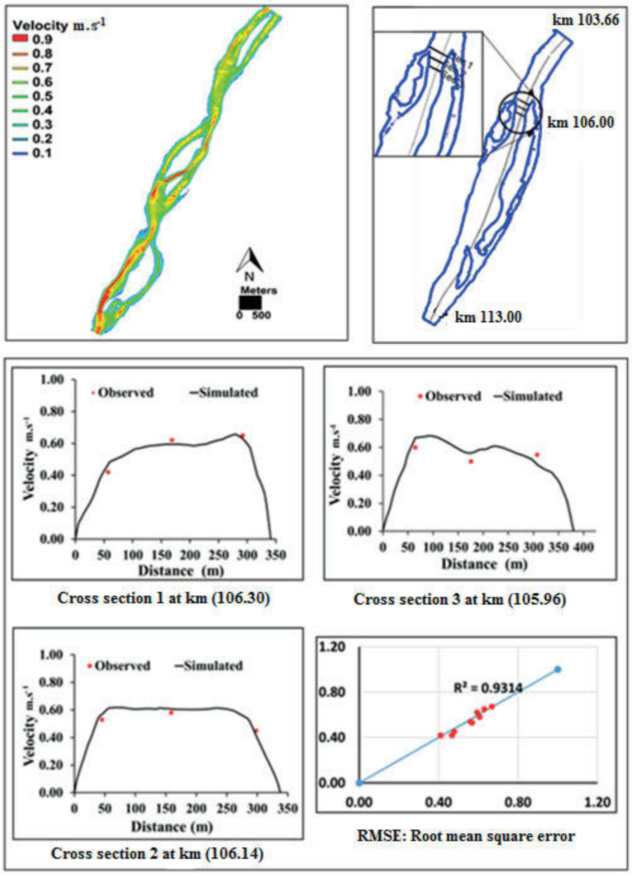

Fig. 4. Flow velocity calibration at cross section 1, 2 and 3; source: own elaboration.

Different error comparison methods were used in practical applications such as determination coefficient (R^2) and root mean square error (*RMSE*). All of these tools are commonly used as standard statistical. The error parameters for the simulated and measured values showed that R^2 equals 0.9314, and *RMSE* equals 0.25. Figure 5 shows the comparison of the measured field velocities and the obtained velocity for the three studied cross-sections.

NAVIGATION CHANNEL OPERATION SCENARIOS

The numerical model was used to predict the effects of the hydrodynamic forces resulting from the movement of vessels in the navigation channel of the Nile River. The characteristics of cargo and container vessels were determined according to the Transport Planning Authority of the Ministry of Transport in Egypt and the JICA Report for 2003. Table 2 showed the vessel characteristics that were used for model simulation. One final parameter that was somewhat independent of the actual physics was the length of the time step chosen for the simulation. The time step was set to the vessel advances one element length per time step. Thus, the length of the time step (Δt) was calculated as:

$$\Delta t = L_e / v_g \tag{10}$$

where v_g is vessel velocity relative to ground.

Table 2. Hydrodynamic parameters and vessel characteristics

Parameter	Measuremnt unit	Value
Hydrodynamic parameters		
Gravitational acceleration	m·s^{-2}	9.81
Water density	kg·m^{-3}	1000
Roughness coefficient	–	0.025
Horizontal eddy viscosity	m^2·s^{-1}	1
Time step	s	5
No. of timestep	s	3000
Vessel characteristics		
Length	m	100
Width	m	15
Depth	m	2.3
Draft	m	1.8
Velocity	m·s^{-1}	3.6

Source: JICA Study Report [2003], modified.

The coordinates of the vessel center were moved each time step according to the vessel's sailing speed and direction and also, according to the vessel's length and width. The computational mesh was constructed such that pressure gradients were applied across the bow, stern, and each side boundary in a manner to maintain the appropriate blockage area (vessel cross-sectional area). The ADH model has been applied to the study reach for evaluating five different alternative scenarios for the vessel traffic in the navigation channel of the Nile River, as shown in Table 3. The model was simulated for both one-way and two-way traffic for the vessel routes traveling direction (i.e., "up bound" or "down bound") for the minimum river flow. The results were used to investigate draw down, the difference of surface water elevation (water fluctuation), clearance of the vessel, vessel induced stresses, and return velocities at the bow and stern of the vessel. The results have been evaluated at the different numbers of the sections and observation points, as shown in Figure 5.

The vessel-induced bed shear stresses are important for its actions on the river bed. The shear stress-induced on the bed by a passing vessel is a large portion of the total bed shear stress, so calculating the vessel induced bed shear stress is important in determining sediment transport patterns. Bed shear stresses attributed to the flow field, including the return currents, were computed using the model simulation. These stresses can be calculated in SMS (with the data calculator) using:

$$\tau f = 1/2\left(\rho c v^2\right) \tag{11}$$

where: τf = bed shear stress due to ambient and return currents, ρ = flow density, c = coefficient of friction for the bed (taken as 0.01 for a sand bed), v = flow velocity magnitude (ambient).

The influence of vessel movement on river morphology can be assessed by analysing the calculated shear stress field.

Table 3. Navigation channel operation scenarios

Scenarios types	Navigability		Navigation channel type		Sailing line direction		Shape
	no vessel	with vessel	one-way	two-way	up bound	down bound	
No vessel	√	—	—	—	—	—	
Scenario 1	—	√	√	—	√	—	
Scenario 2	—	√	√	—	—	√	
Scenario 3	—	√	—	√	√	—	
Scenario 4	—	√	—	√	—	√	

Source: own elaboration.

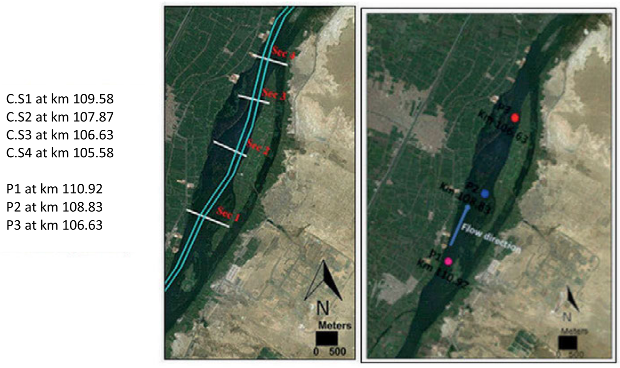

Fig. 5. Draw down cross-sections and velocity observation points; source: own elaboration

RESULTS AND DISCUSSION

DRAW DOWN AND SURFACE WATER ELEVATION

Draw down percentage, under keel clearance, and surface water elevation were calculated at four sections; at km 109.58, km 107.87, km 106.63, and km 105.58 for original, one-way, and two-way scenarios. Each scenario included calculating the draw down percentage for both up bound and down bound. The obtained results were presented as shown in Figures 6, 7, and 8. The values for all cross-sections are shown in Table 4 and Figure 9.

The draw down generated along a navigation channel for the different vessel traffic scenarios were simulated with the ADH model. For each scenario, the draw down percentage for both vessel sailing directions (up bound and down bound) was calculated. The obtained results showed that the maximum draw down occurred at the rive island cross-section No. 2, which had the narrowest channel width and the shallowest water depth. In opposite, cross-section No. 3 had the lower draw down because it was the widest channel width and the deepest water depth. The draw down percentages for all sections were not affected by the vessel traffic direction because the draw down was linked to the vessel draft value, which was a fixed value for all model scenarios. It was observed that the higher draw down values occurred at the narrower river reaches. These values also occurred at higher flow discharges.

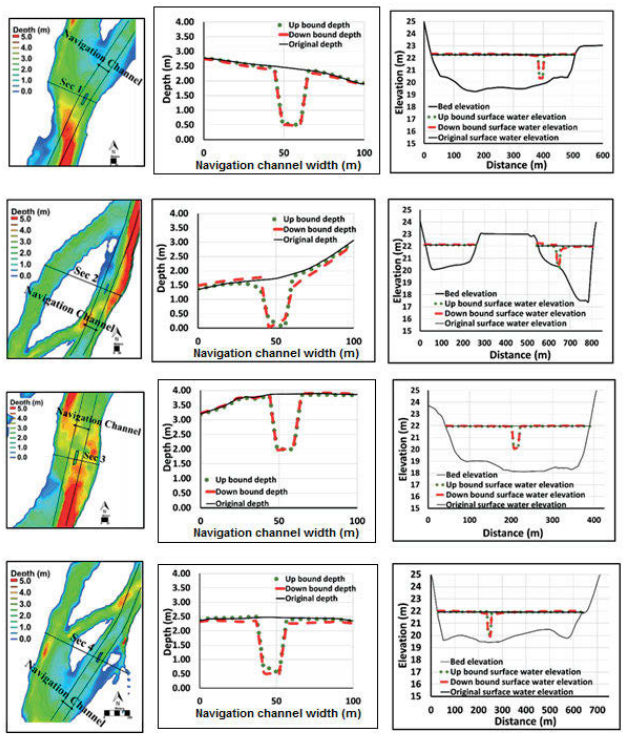

Fig. 6. Model plan of depth, draw down, and difference of surface water elevation for cross-section No. 1, 2, 3 and 4 at one-way scenario; source: own study

UNDER KEEL CLEARANCE

The under-keel clearance was computed for the same four sections under the different alternative scenarios. The under-keel clearance of four sections could be arranged according to morphological risk as following; firstly section No. 2 as the worst section, where there was no clearance under the vessel, followed by section No. 4 where the clearance was 46.5 cm in one way scenario and 36.5 cm in two way scenario, then section No. 1 where the clearance was 54.2 cm in one way scenario and 50.9 cm in two way scenario, eventually section No. 3 where the clearance was 183.2 cm in one way scenario and 155 cm in two way scenario. The results showed that cross-section No. 2 is considered to be the worst section for the navigation status, while section No. 3 was the best section.

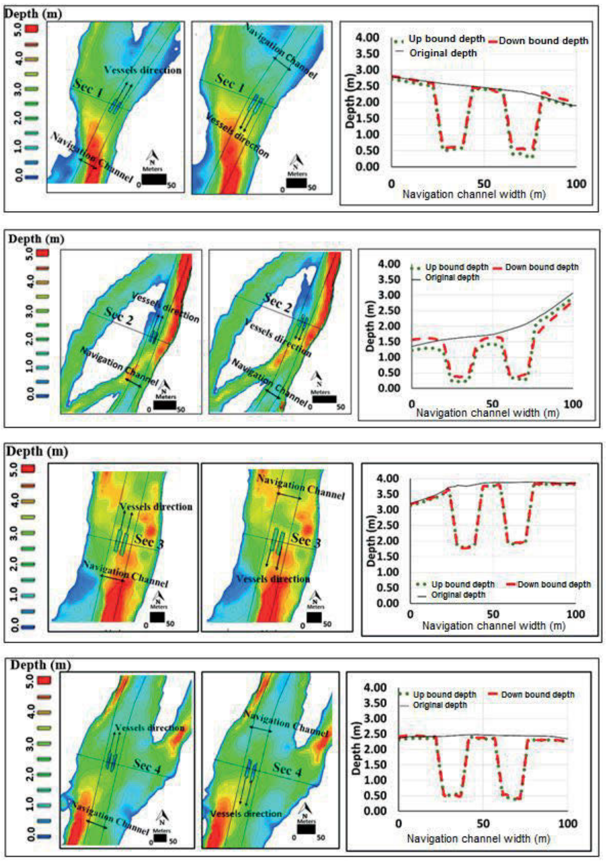

Fig. 7. Model plan of depth and draw down, and difference of surface water elevation for cross-section No. 1, 2, 3 and 4 at two-way scenario; source: own study

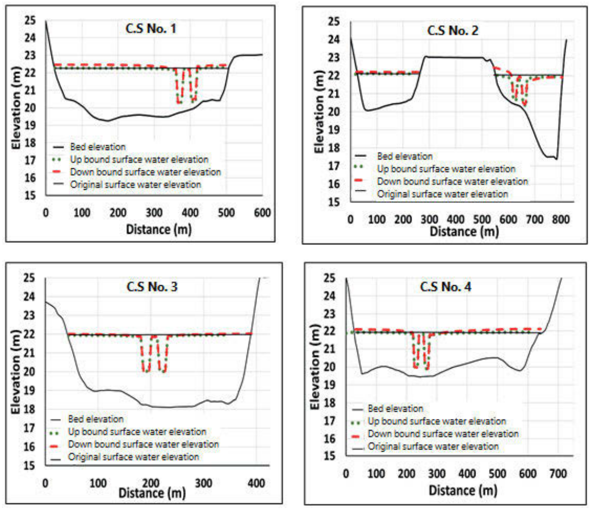

Fig. 8. The difference of surface water elevation for cross-section No. 1, 2, 3 and 4 at two-way scenario; source: own study

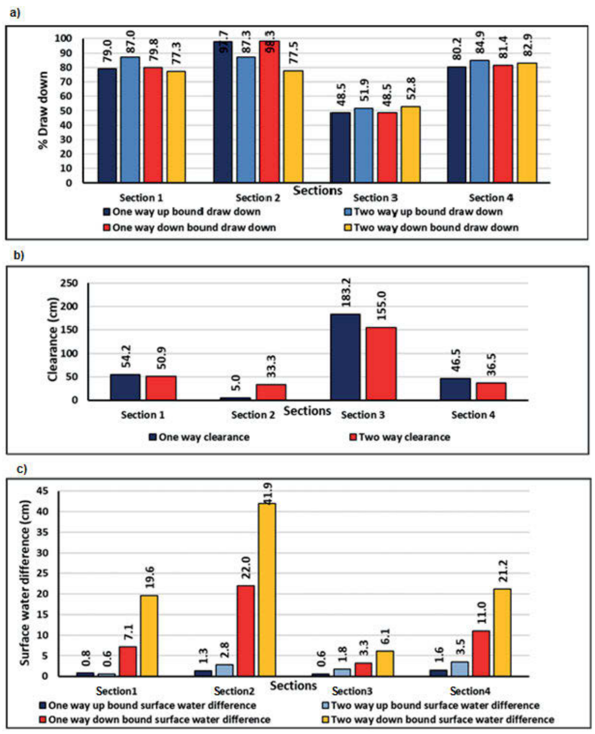

Fig. 9. Vessel hydrodynamic effects: a) vessel draw down percentage, b) vessel under keel clearance, c) the difference of surface water elevation of the vessel histogram; source: own study

DIFFERENCE IN SURFACE WATER ELEVATION

The ADH model was used to predict the maximum surface water elevation fluctuation generated by the moving vessels for the different scenarios.

The difference in surface water elevation expresses fluctuation that occurs as a result of the passage of vessels. The fluctuation produced in the case of a vessel passing opposite the direction of the current (down bound surface water difference) was higher than the surface water fluctuations produced in the case of a vessel passing with the direction of the current (up bound surface water difference). The sections could be arranged from the higher to the lowest for the fluctuation as follows;

Table 4. Draw down percentage, under keel clearance, and surface water elevation

Section number	Draw down percentage at vessel traffic and vessel sailing direction				Clearance at vessel traffic (cm)		Surface water difference at vessel traffic and vessel sailing direction (cm)			
	one way traffic		two way traffic		one way	two way	one way traffic		two way traffic	
	% up bound	% down bound	% up bound	% down bound			up bound	down bound	up bound	down bound
1	79.0	79.8	87.0	77.3	54.2	50.9	0.8	7.1	0.6	19.6
2	97.7	98.3	87.3	77.5	0.0	33.3	1.3	22.0	2.8	41.9
3	48.5	48.5	51.9	52.8	183.2	155.0	0.6	3.2	1.8	6.1
4	80.2	81.4	84.9	82.9	46.5	36.5	1.6	11.0	3.5	21.2

Source: own study.

section No. 2, section No. 4, section No. 1, and section No. 3. It was concluded that section No. 2 was the higher fluctuation, and section No. 3 was the lowest surface water fluctuations. The values ranged from 6.3 to 41.9 cm. It was predicted that the fluctuation in the two-way scenario was double of fluctuations of the one-way scenario for all sections because the two vessels produced relatively large waves. It was observed that for upstream-bound and downstream-bound vessels, the water-level fluctuations did not show significant differences, and the largest difference of surface water elevation was produced at the river island cross-section.

RETURN VELOCITY

Velocity difference values were calculated at three observation points at km 110.92, km 108.83, and km 106.63 for both one-way and two-way scenarios. Each scenario included measuring the velocity for both up bound and down bound. The obtained results were presented in Figures 10, 11, and 12.

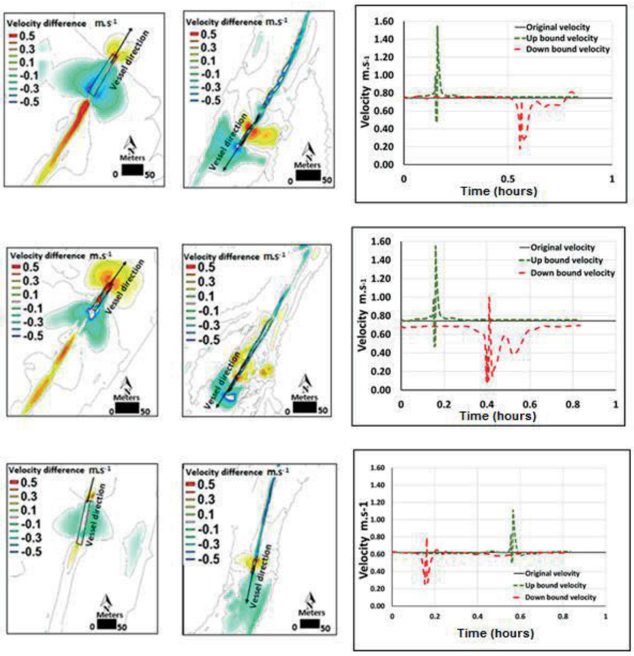

Fig. 10. Velocity difference at point No. 1, 2, and 3 (km 110.92, 108.83 and 106.63), at one-way scenario; source: own study

Simulations of the vessel traffic in the navigable waterway of the study reach along the Nile River were performed for up bound and down bound navigation directions.

The computed return velocities difference at these points between the bow and the stern were analysed for different alternative scenarios, as shown in Figure 13. The figure showed that the return velocity increased at the bow and stern of the vessel if it passed with the direction of the flow, but the velocity decreased at the bow and stern of the vessel if the passage of the vessel was against the direction of the flow. It was concluded that the velocity in the case of a two-way navigation channel was higher than the case of one way, where the pressure of two vessels was greater than the pressure of one vessel. The highest return velocities occurred at the river island site.

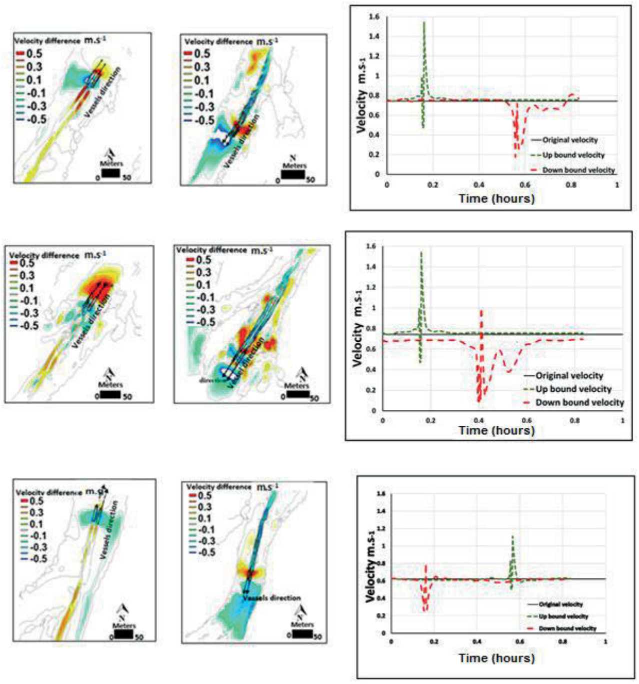

Fig. 11. Velocity difference at point No. 1, 2, and 3 (km 110.92, 108.83 and 106.63), at two-way scenario; source: own study

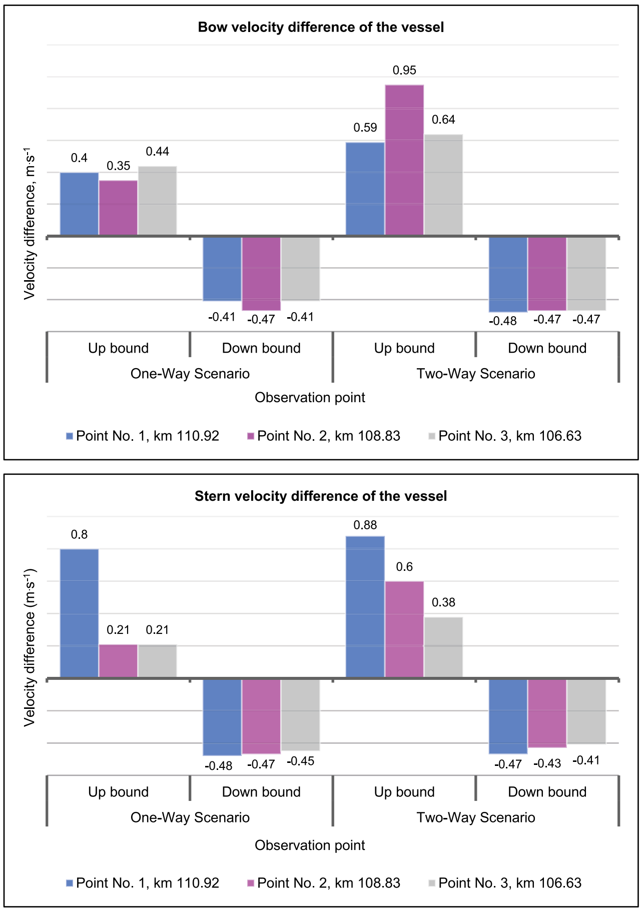

Fig. 12. Histogram of the velocity difference at bow and stern of the vessel; source: own study

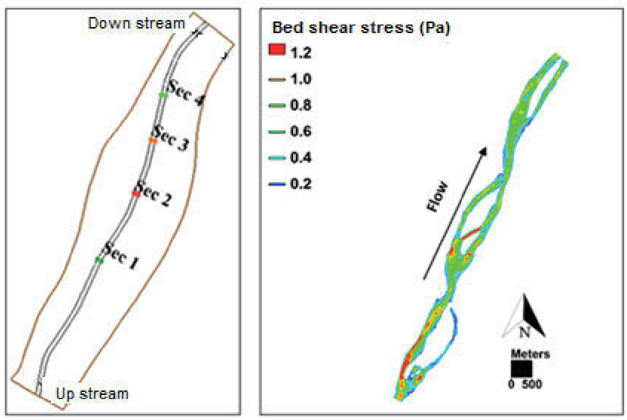

Fig. 13. Original bed shear stress plane; source: own study

VESSEL-INDUCED BED SHEAR STRESSES

The numerical ADH model has been applied to calculate the bed shear stresses due to the vessel movement in the Nile River. The obtained results for the original bed shear stress without operating the navigation channel with vessels were shown in Figure 13. The results of operating navigation channel with vessels for several scenarios were presented for the cross-sections in Figure 14a and the longitudinal section in Figure 14b.

The related stresses affected the near-bed boundary layer, and bed shear stress increased gradually, leading to the resuspension of fine sediments.

It was found that section No. 2 had the highest shear stress where this section had the narrowest width and the lowest depth. And this section was considered more prone to erosion. But section No. 3 had the lowest shear stress where this section had the widest width and the largest depth so this section was considered less prone to erosion. It was concluded that primary waves increased the bed shear stresses around the vessel, especially their zone close to the vessel sailing line.

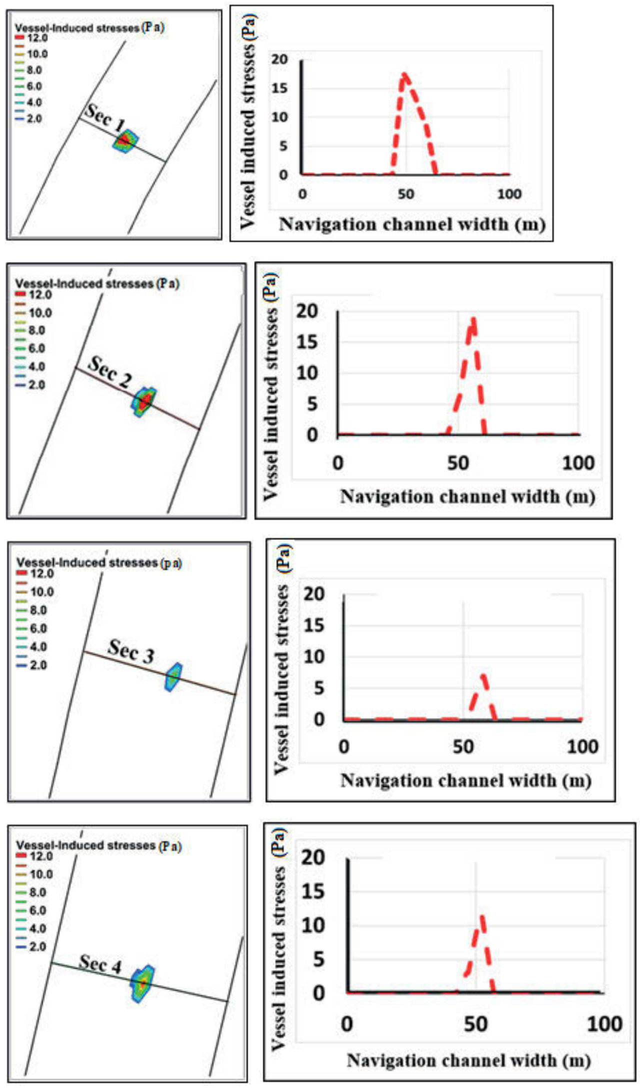

Fig. 14. Vessel-induced stresses at sections 1, 2, 3, and 4; source: own study

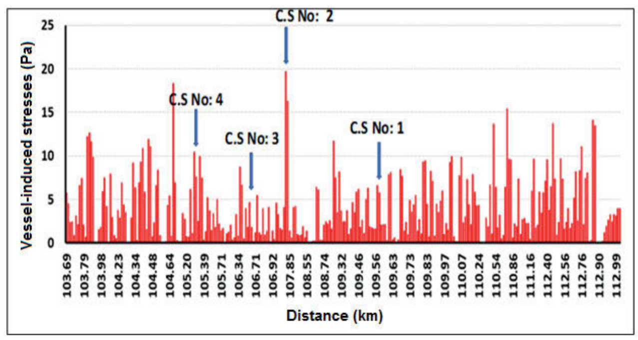

Fig. 15. Longitudinal section of vessel-induced stresses; source: own study

CONCLUSIONS

In this paper, a methodology to simulate and analyse the hydrodynamic effects due to a vessel passage has been conducted. The adaptive hydraulics model (ADH) was an appropriate approach for studying and predicting the effects generated by a vessel passage. This methodology has been applied to several scenarios, which were up bound one-way, down bound one-way, up bound two-way, and down bound two-way.

The section having the narrowest width and the lowest depth was associated with the largest draw down percentage, which had the values of 98.3% and 87.3% in one-way and two-way scenarios. The section having the widest width and the largest depth was associated with the least draw down percentage, which had the values of 48.5% and 51.9% in one-way and two-way scenarios.

Under keel clearance, as the reverse of draw down, is an essential issue that strongly influences the Nile River transportation efficiency and expresses morphologic risk. It was concluded that the section having the narrowest width and the lowest depth was the worst section for under keel clearance, which had the values of 5.0 cm and 33.3 cm in one-way and two-way scenarios. Also, the section having the widest width and the largest depth was the best section, where its clearance values were 183.2 cm and 155.0 cm in one-way and two-way scenarios.

The fluctuation produced in the case of down bound was greater than that produced in the case of up bound. The section having the narrowest width and the lowest depth was associated with the largest fluctuation, which had the values of 22.0 cm and 41.9 cm in one-way and two-way scenarios. Also, the section having the widest width and the largest depth was associated with the least fluctuation, which had the values of 0.6 cm and 1.8 cm in one-way and two-way scenarios.

The velocity increased at the bow and stern of the vessel for up bound cases, and it decreased for down bound cases. Also, the velocity in the case of the two-way scenario was greater than that in the case of a one-way scenario.

The section having the narrowest width and the lowest depth was associated with the highest shear stress. Thus, this section was considered more prone to erosion. On the other hand, the section having the widest width and the largest depth was associated with the lowest shear stress. So, this section was considered less prone to erosion.

However, the results will be useful for preliminary assessment of the relative impact of vessel traffic in the river hydrodynamics and for identification of potential areas along the riverbed that are likely to be sensitive for the river morphological considerations. The numerical model provides visualization products that help to understand the complicated forces produced by vessels moving in a navigation channel and can be used for decision-making policies to improve navigational safety, to ensure a sustainable future of river navigation, and optimize the design and management of inland navigation in the Nile River.

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