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Cover Page Footnote

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Morphological Changes Downstream Beni-Suef Bridge on the Nile River in Egypt

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***Abstract-* The construction of the Beni-Suef bridge, spanning 550 meters over the Nile River, resulted in sediment accumulation and hindered navigation. This study investigates the causes of the morphodynamic changes and explores the impact of dredging as a mitigation measure through the area which extended approximately 2.6 kilometers downstream the bridge. A one-dimensional numerical model (HEC-RAS) was employed, utilizing bathymetric surveyed cross-sections from 1982, 2002, and 2004, along with discharge data from downstream Assuit Barrage and water levels from upstream Delta Barrage as boundary inputs. The model was calibrated and validated using measured water and bed levels. Sediment properties and bed composition were incorporated based on samples collected by the Nile Research Institute. Three distinct sediment load formulas were utilized to identify the most suitable one for accurately capturing the physical characteristics of the studied area. After validation, the model was utilized to forecast cross sections for 10 and 20 years, in case of with and without dredging scenarios. The dredging approach was aligned with the navigation requirements in the study region. The study reveals that the Ackers-White sediment formula showed the closest match with minimal differences in deposition and erosion compared to other formulas. Besides, the study area is predominantly experiencing deposition, which is projected to continue in the future. In addition, the predicted sediment volumes were concentrated at the beginning of the study area in both scenarios. The findings indicate also that most depositions occurred in the initial ten years approaching a state of morphodynamic equilibrium. Moreover, the results showed that the dredging reduced rates of sedimentation by 23% and 26% after 10 and 20 years, respectively, which provide an effective solution for mitigating sedimentation along the navigation path in the study area.**

***Keywords-* Morphology at bridges; sedimentation; erosion; navigation bottlenecks; Hec-Ras model.**

I. INTRODUCTION

Building bridges is crucial for establishing a transportation system that can traverse streams or waterways. However, the construction and existence of these structures has significant impacts on the riverbed morphology and hydrodynamics [1-7]. Bridges can alter the flow of water, which can lead to changes in flow velocity, bed shear stresses, sediment transport, and deposition patterns due to the narrowness of the waterways at the bridge construction sites [8-11]. Additionally, the presence of a bridge can create a physical obstruction that can affect the natural channel shape and dimensions of the river [12-14]. Besides, the construction of bridges with an excessive number of piers can lead to numerous negative impacts. These include heavy sedimentation on the riverbed, increased frequency of flooding, and reduced water carrying capacity, thereby affecting river navigation [15-19]. In alluvial channels, the presence of submerged structures such as bridge piers can disrupt the flow pattern, causing localized erosion in those areas [20]. Hence, it is essential to consider the possible consequences of bridge construction on river morphology and employ suitable measures to alleviate any negative impacts.

In 2006, Sadek et al. [21] performed a mathematical analysis to examine the navigation challenges caused by the construction of the El-Menia bridge on the Nile River in Egypt. Their findings highlighted the importance of dredging the main channel on the east side of the study area and removing the submerged islands in the middle of the channel. These measures were found to be necessary in preventing the growth of grass during the minimum discharge season and consequently reducing sediment

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deposition. In 2012, Kothyari et al. [22] investigated sedimentation in the vicinity of bridge piers. They found that sediment deposition near piers could lead to channel adjustments and affect the sediment transport at the downstream of the bridge.

In 2017, Islam et al. [23] assessed the effects of the bridge on the dynamics of bar morphology in the Jamuna River in Bangladesh. They utilized time-series satellite images to analyze the development of bars in the study area before and after the construction of the bridge. The findings revealed a significant 14.63% increase in the bar area during the post-bridge construction period. Han et al. [24] conducted a numerical study in 2018 to assess the impact of bridge construction on flood control in a constrained section of the Weihe River in China. By evaluating three distinct plans, particularly at the Xianyang reach, the findings emphasized the significance of implementing a successful dredging project to widen the river and reduce water levels, thereby enhancing the river's flood control capacity. Biswas and Banerjee [25] investigated, in 2018, the impact of bridges on the morphology of the Barakar River in India. The study showed that, downstream of the bridges, there was an observed increase in the river channel's gradient, width, and depth. In 2019, Sarma and Talukdar [26] conducted a study to examine the influence of the Bogibeel bridge construction on the morphology of the Brahmaputra River in northeastern India. Utilizing satellite imagery analysis spanning 25 years, the researchers investigated variations in the river channel width before and after the bridge's construction. The study findings revealed that the bridge's construction led to a narrowing of the river channel, resulting in an accelerated rate of riverbed erosion near the bridge and consequential morphological alterations downstream the bridge. In 2021, Biswas and Pani [27] used the HEC-RAS model to study the impact of bridge construction on flow characteristics and sedimentation patterns in India's River Chel. Their analysis revealed varying effects on river morphology, with the upstream side experiencing an increased bed section level and the downstream side showing the opposite trend. Bottleneck conditions led to increased flooding, resulting in bank erosion and significant consequences for the surrounding land.

Overall, bridges can have significant impacts on the morphology of rivers. However, with proper design and mitigation measures, the impacts of bridges on river morphology can be minimized, allowing for the safe and efficient transportation of people and goods while maintaining morphological integrity of the river system.

The goal of this study is to understand the impact of the river flow on the morphological changes downstream (DS) of the Beni-Suef bridge in Egypt. This goal was addressed through a numerical modelling study using a one-dimensional (1D) model. Two main objectives guided the analysis: studying the morphodynamic changes corresponding to a time-dependent discharge hydrograph of the river flow (anticipant flood conditions), and the morphodynamic changes post dredging. The navigation depth DS Beni-Suef bridge was used as an indicator for the efficiency of the mitigation solution. Furthermore, the model was used to forecast future morphological changes within the study area and examine the long-term impact of dredging operation.

II. SITE DESCRIPTION

The study area extends for approximately 2.6 kilometres (Km) DS of the Beni-Suef bridge, between kilometre markers 118.730 and 116.130 located from upstream (US) of the El-Roda Gauge Station (RGS). The Beni-Suef bridge itself, which constructed in 1984, is positioned at km 118.900 upstream of RGS and km 808.1 downstream of the Old Aswan Dam (OAD), spanning 550 meters across the Nile River from the left to the right bank. This section falls within Reach Four of the Nile River, as shown in Fig. 1. The bridge rests on eight piers, each 1.4 meters thick. The span between the first two piers, starting from the left bank, measures 50 and 80 meters respectively, while the remaining openings toward the right bank are each 60 meters wide.

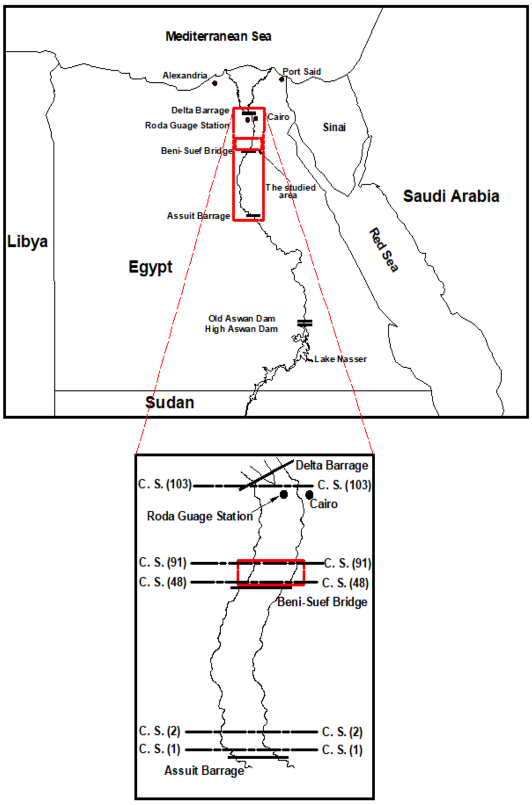

Figure 1. Location map of the studied area and Beni-Suef bridge over the Nile River, Egypt.

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III. DATA COLLECTION

The geometric data generated in this study hold significant importance for the current research. A hydrographic survey was carried out by the Nile Research Institute (NRI) along reach four, spanning between the river banks, during the years 1982 [28] and 2004 [29]. This survey encompassed approximately 103 cross sections (c.s.) at intervals of 6000 m, starting from Assuit Barrage and ending at Delta Barrage. Additionally, a higher-resolution survey was conducted at a frequency of approximately every 60 m across the entire study area, covering 2.60 km from c.s. 48 to c.s. 91, as shown in Fig. 1. These cross sections were utilized in the mathematical model for calibration and verification purposes. The developed contour maps based on these measurements are shown in Fig. 2 and Fig. 3. All vertical levels presented in this study are referenced to mean sea level (MSL).

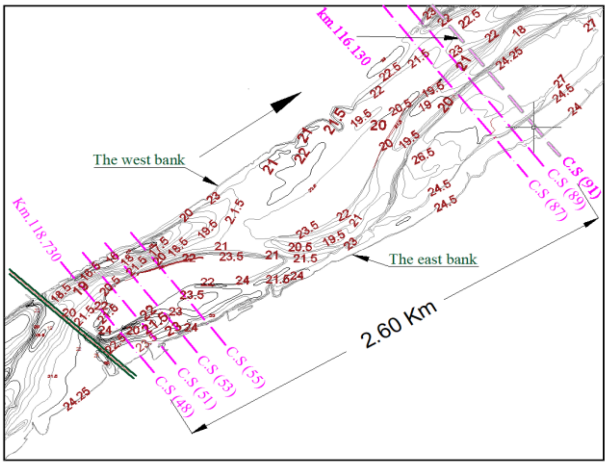

Figure 2. Bathymetric contour map DS Beni-Suef bridge for the year 1982.

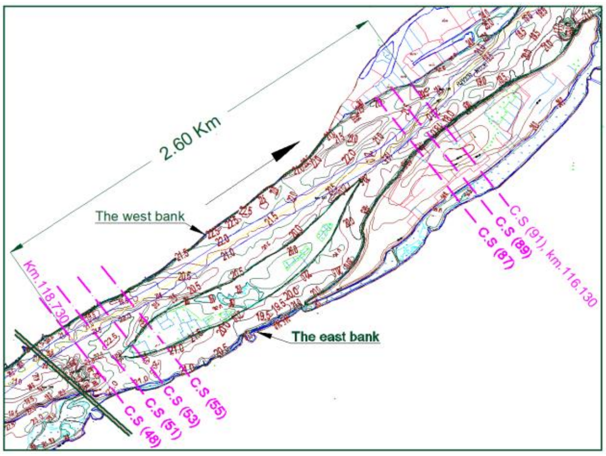

Figure 3. Bathymetric contour map DS Beni-Suef bridge for the year 2004.

IV. EROSION AND SEDIMENTATION ANALYSIS

The bathymetric surfaces for the study reach, illustrating the area downstream of the two blue lines representing the bridge, are plotted as shown in Fig. 4 and Fig. 5 for years 1982 and 2004, respectively. While Fig. 6 depicts the resulting morphological changes over that period.

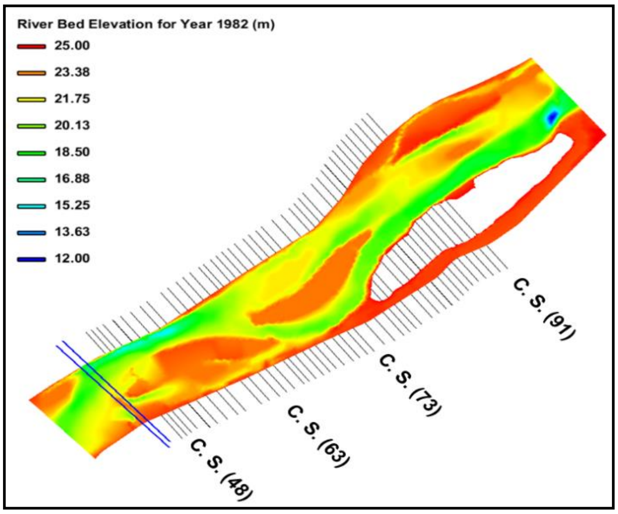

Figure 4. River bed elevation for year 1982 (m, MSL).

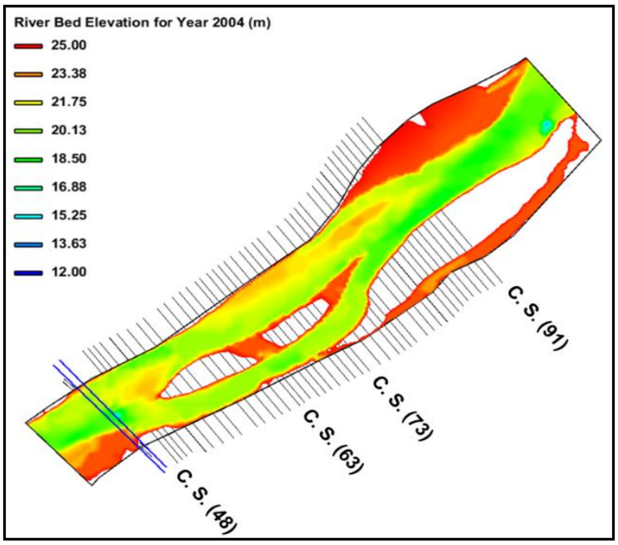

Figure 5. River bed elevation for year 2004 (m, MSL).

Based on the observations in Fig. 6, it is evident that an erosion region exists DS of the bridge, located on the eastern side of the river near the bank. Additionally, there is a deposition of sediment in the mainstream, leading to the formation of an island DS of the bridge. The study area in the period 1982/2004

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experienced an average rise in bed levels of approximately 2.0 m, resulting in navigation bottlenecks. Also, in cases of erosion, the average rise in bed levels was reduced to 2.0 m.

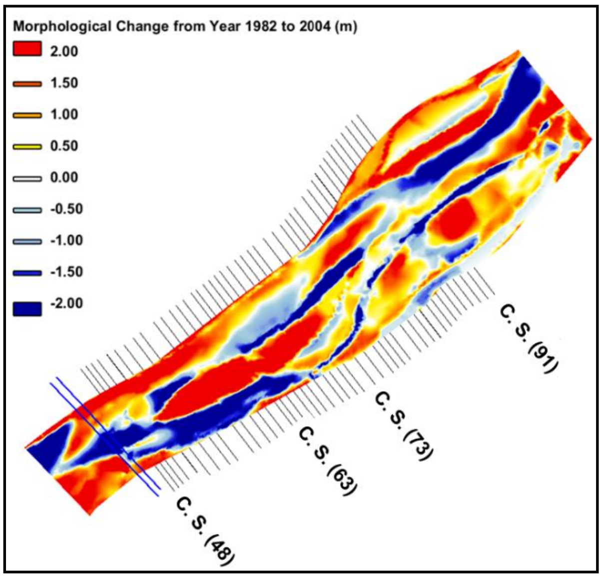

Figure 6. Morphological change from 1982 to 2004 (m, MSL).

For further scrutiny, the variations between the bathymetric surfaces were visualized along three selected cross sections as examples, as illustrated in Fig. 7, Fig. 8, and Fig. 9. The estimated average volumes of sediment deposition and erosion within the study area between 1982 and 2004 were approximately 253,085 m³ and 90,795 m³, respectively. The results indicate that sediment deposition was the dominant morphological process throughout the studied period.

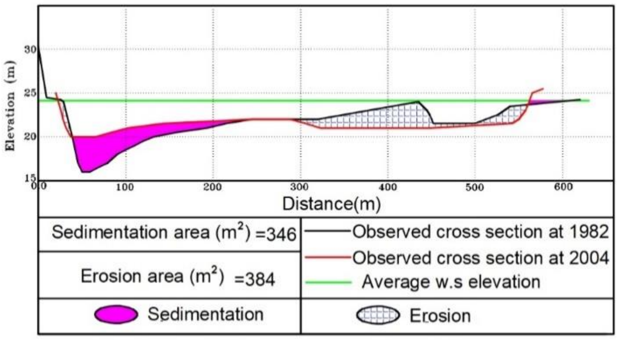

Figure 7. The deposition and erosion at c.s. 49, km (118.690) US RGS.

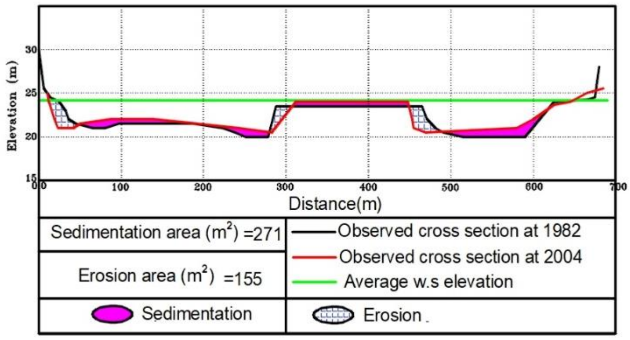

Figure 8. The deposition and erosion at c.s. 91, km (116.130) US RGS.

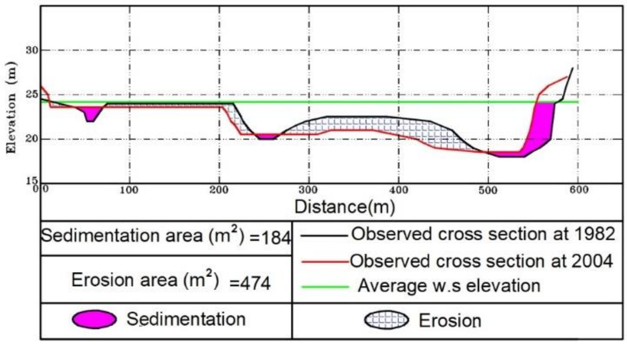

Figure 9. The deposition and erosion at c.s. 75, km (117.020) US RGS.

V. HEC-RAS MODEL

HEC-RAS is a 1D model able to simulate steady and unsteady flow, besides, sediment transport for movable boundary conditions. Initial conditions are established from the unsteady flow at the upper end of the reach four and the corresponding water surfaces at DS the reach. In addition, cross sections were placed at representative locations to describe the changes in geometry. The tolerance for water surface calculations is employed to assess the variance between the observed and estimated water surface elevations at various cross sections. In the model framework, a sediment control volume is associated with each c.s. by bed material gradation templates. These templates are used in different sediment transport functions through the model calibration and verification. These functions are Ackers-White, England-Hansen, and Yang formula [30].

A. Model calibration and verification

A hydrodynamic and morphodynamic calibration was carried out over the reach four that extends from Assuit Barrage to Delta Barrage (approximately 410 km.). The hydrodynamic

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calibration was carried out using measured water levels at specified gage stations along this reach, while the morphodynamic calibration was done using surveyed bed levels in the years 1982 [28] and 2002 [31]. The surveyed bed levels of the year 1982 were used as an initial input to the model. The model was executed for the time period spanning from 1982 to 2002, employing various sediment transport equations which mentioned in the "HEC-RAS Model" section. The latter period between the years 2002-2004 was sued for validation. Details on the calibration and verification are listed in the following subsections.

B. Flow model calibration

A model was firstly calibrated to one set of observed data and then validated with a different set. The model was run once with the bed levels from the year 1982 and another with the bed levels from the year 2002. Water discharges of 70 M.m^3/day for low flow and 181 M.m^3/day for high flow were imposed as boundary conditions for the calibration stage. The model was also calibrated against Manning's coefficient (n) by changing its value at every cross section along the reach four. This calibration was performed through a comparison between measured and simulated water levels until an adequate calibration was obtained at different values of n which varies from 0.022 to 0.038. These values produced a minimum summation of errors, defined as: Percentage of error = $\sum$(P – M) / M, where: P (predicted water surface for each point) and M (measured water surface for each point), with accepted percentage of error of ±5 %. Fig. 10 showed the modelled water levels compared to the measured values. In addition, it indicated that the error in the model output results corresponding to low flow was in average equal to 0.05 % while it reached 0.08 % in case of high flow.

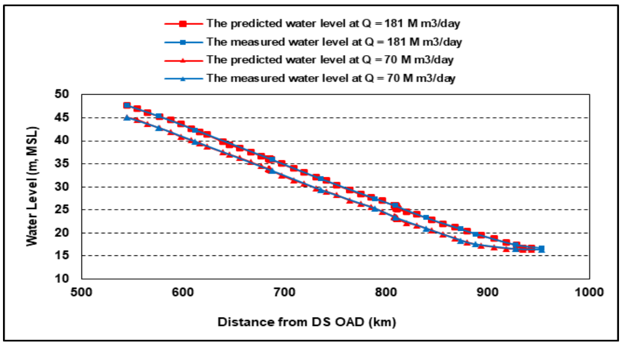

Figure 10. The modelled water levels compared to the measured values from Assuit Barrage to Delta Barrage at high and low flows

C. Morphology model calibration phase

The monthly average discharge was imposed as an unsteady-boundary condition. The discharge reflects the measured flow DS of Assiut barrage between the years 1982 and 2002. Sediment samples of the fourth-Nile River reach which collected and analyzed by NRI [28, 31] were used to characterize the sediment properties in the model. A variable bed composition was imposed for different cross sections as an initial condition, where the percentage of the selected samples for each size class is listed as follows in Table 1.

Table 1. Bed composition used in the model corresponding to every size class [31]

Cross Sections	Percentage of the grain class (%)			
	Fine Sand	Medium Sand	Coarse Sand	Gravel
1:4	7.9	68.53	20.95	2.62
5:9	12.34	70.33	16.65	0.68
10:14	11.38	78.19	9.96	0.47
15:20	13.10	64.93	20.82	1.15
21:25	5.24	49.15	32.97	12.64
26:31	9.08	77.41	13.46	0.05
32:38	3.23	71.82	22.79	2.16
39:44	6.17	63.20	24.76	5.87
45:57	14.62	66.53	16.74	2.11
58:66	7.25	64.44	17.63	10.68
67:73	4.11	50.65	32.21	13.03
74:79	8.56	54.28	22.83	14.33
80:92	9.60	79.06	10.78	0.56
93:98	10.30	58.21	28.55	2.94
99:103	18.80	74.80	6.33	0.07

The bed composition is characterized with fine, medium, and coarse sand, in addition to gravel. Different run trials of the model were carried out using three different bed-material sediment load equations in order to select the sediment model formula that best fits the area under study. The selection was based on comparing the resulting cross-sections with the surveyed data. Based on this comparison, it was found that Ackers-White formula shows a better match in comparison with England-Hansen and Yang formulae. These results are demonstrated as an example for cross sections numbers 61 and 67 in Fig. 11 and Fig. 12 respectively. In case of deposition, the difference between measured and simulated bed levels across the two selected cross-sections are in average of 0.4%, 4.2% and 5.5% for Ackers-White, England-Hansen, and Yang, respectively. While for erosion, the differences for the same models listed above amounted to an average of 1 %, 4.5%, and 4.3%, respectively.

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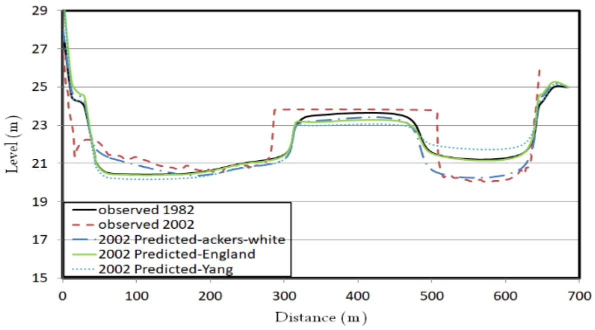

Figure 11. Observed vs simulated bed levels, c.s. 61, at km (117.875) from RGS.

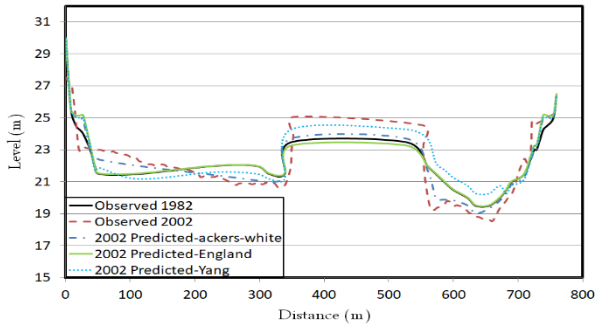

Figure 12. Observed vs simulated bed levels, c.s. 67, at km (117.550) from RGS.

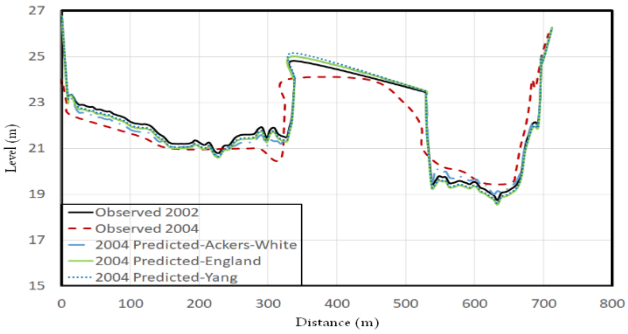

Figure 13. Observed vs simulated bed levels, c.s. 64, at km (117.710) from RGS.

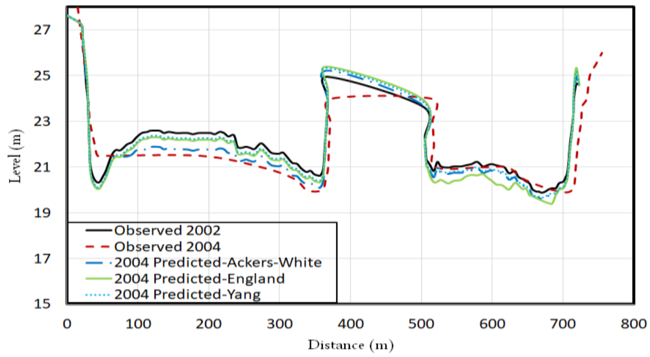

Figure 14. Observed vs simulated bed levels, c.s. 74, at km (117.095) from RGS.

D. Morphology Model Validation

The model was also validated using the surveyed cross-sections of the year 2004, starting the model with surveyed bed levels of the year 2002. The sediment parameters in the model were characterized as in calibration phase, using the sediment size classes and initial compositions listed in Table 1. The validation was carried out by comparing the surveyed to simulated cross-sections as demonstrated for an example in Fig. 13 and Fig. 14 for the two selected cross sections numbers 64 and 74 respectively, where the Ackers-White sediment model still showed the best fit. The comparison showed that in the case of deposition, Ackers-White represents a 1.5 % difference, England-Hansen represents a difference of 3.4%, while Yang represents a difference of 4%. In case of erosion, Ackers-White represents difference 1.1 %, England-Hansen represents difference 3%, and Yang represents difference 2.7%. All the previous values are calculated in average values across the section.

VI. EVALUATION OF THE EXISTING NAVIGATIONAL PATH

The design of the navigation channel DS of Beni-Suef bridge aimed to achieve a minimum width of 100 m and a water depth of at least 2.3 m according to the navigational requirements of River Transport Authority (RTA) [32]. From field observations and as a result of morphological changes, it was discerned that the deposition in the thalweg at study area can potentially cause navigation difficulties as shown in Fig. 15 and Fig. 16. The depositions reduced the width of the navigation channel and decreased the water depth, which varies between a maximum of 2.3 m and a minimum of 0.45 m thus instigating bottlenecks. To maintain the minimum water depth of 2.3 m in the studied area, the calculated dredging volume was approximately 229,145 m^3. Water surface elevation along the study reach was measured before and after dredging as showed in Fig. 17. To achieve the desired objectives of the navigation requirements, a study reach DS this bridge was selected through two field trips. The first trip was before dredging and the second trip was after dredging. The resulting water surface slope before and after dredging showed a difference of 6 cm at the upstream of the study reach at km 119.23, as demonstrated in Fig. 17. Despite this minor difference

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in water surface elevation, the after-dredging depths are considered sufficient for navigation.

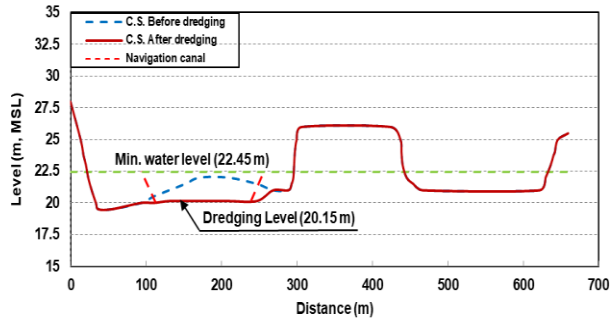

Figure 15. Navigation channel at c.s. 54, km (118.39) from RGS.

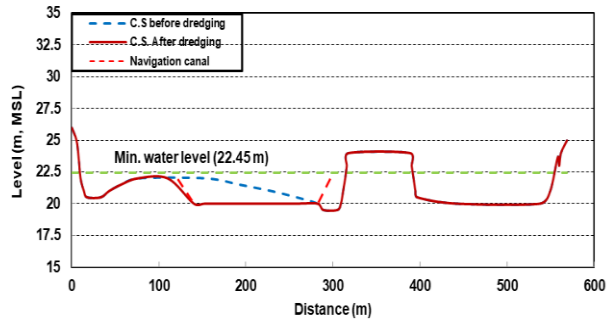

Figure 16. Navigation channel at c.s. 77, km (116.92) from RGS.

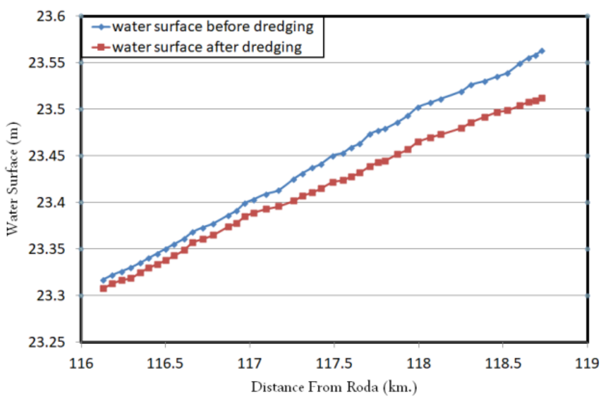

Figure 17. Water surface at the studied area before and after dredging.

VII. LONG TERM MORPHOLOGICAL CHANGES

The calibrated/validated HEC-RAS model was used to simulate the morphological changes DS of the Beni-Suef bridge, over a 10-year period between years 2004 and 2014. An additional scenario was carried out to predict the bed changes of the study reach between the years 2014 and 2024. A time-dependent water discharge hydrograph was imposed for the simulation period, discussed below in the boundary conditions section.

A. Model setup and boundary conditions

The bathymetric and hydraulic data were collected to establish the initial and boundary conditions of the numerical model. The bed composition, which demonstrated before in Table 1, was used also in these simulations. Cross sections, representing the entire study reach, were digitized from the surveyed contour maps in the year 2004. The digitized bathymetry was post-processed into 103 cross-section which covers the fourth reach and imposed in the 1D model. Variable discharge DS Assuit Barrage was collected during the period from 2000 to 2020 as well as the water levels corresponding the normal depth in the DS of the study reach, as illustrated in Fig. 18 and Fig. 19. The discharge and water levels were imposed as boundary conditions in the model, both for the before and after dredging scenarios.

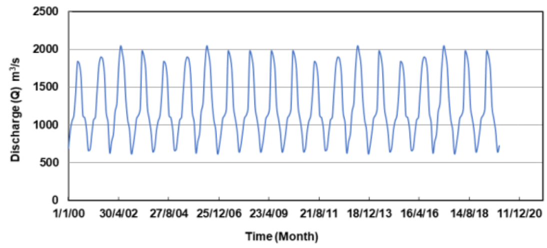

Figure 18. Monthly discharge hydrograph DS Assuit Barrage from year 2000 to 2020.

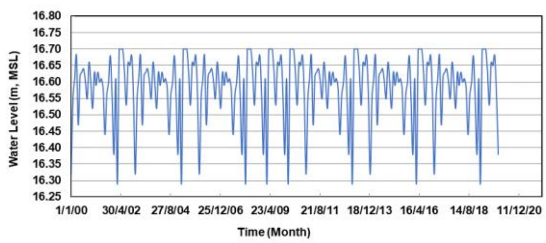

Figure 19. Monthly water level hydrograph US Delta Barrage from year 2000 to 2020.

B. Morphological changes before and after dredging

At the 44-cross section located DS of the Beni-Suef bridge, an analysis of the average changes in sedimentation and erosion volumes was conducted. The results include both dredging and non-dredging scenarios, with simulation periods spanning 10 years (from 2004 to 2014) and 20 years (from 2004 to 2024), as depicted in Fig. 20 and Fig. 21. Positive values in these figures indicate deposition quantities, while negative values represent erosion amounts.

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The results of the 10-year simulation period in the absence of human intervention, referred to as the "without dredging scenario", demonstrate that there was 659,161 m^3 of sedimentation and -242,246 m^3 of erosion in the study area, as shown in Fig. 20. This resulted in a net difference of 416,915 m^3, indicating an overall trend towards deposition. The sediment volumes were found to be higher at the beginning of the studied area behind the bridge, while the rate of erosion was greater at the end of the area. The highest rate of sedimentation was observed at c.s. 52, with around 62,000 m^3, whereas the most significant amount of erosion occurred at c.s. 85, with approximately -38,000 m^3.

In the 20-year simulation period, the study area continued to experience an overall trend towards deposition, with a net deposition of 529,125 m^3, which is a 27% increase compared to the 10-year simulation. The sedimentation and erosion volumes were 832,150 m^3 and -303,025 m^3, respectively, representing a 26% and 25% increase compared to the 10-year simulation. Similar to the 10-year simulation, higher sediment volumes were observed at the beginning of the study area, while erosion rates were greater towards the end. C.s. 52 had the highest sedimentation rate, with approximately 66,000 m^3, which is a 6.5% increase compared to the 10-year simulation. In contrast, c.s. 85 experienced the largest amount of erosion, with around -42,000 m^3, which is an 11% increase compared to the 10-year simulation.

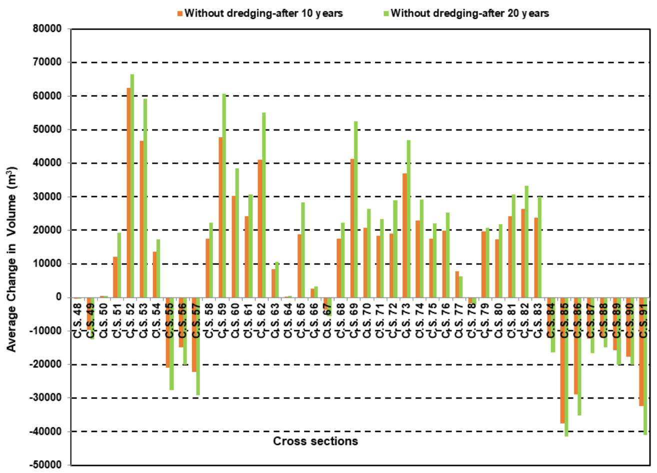

Figure 20. Average volume change of sedimentation and erosion at the 44-cross sections DS Beni-Suef bridge in case of without dredging scenario.

Regarding the dredging scenario, as illustrated in Fig. 21, the model implemented a dredging method that adhered to the criteria previously specified by RTA, aiming to meet the navigation requirements across the entire study area. The results of this scenario showed that the study area experienced a net deposition of 320,566 m^3 during the 10-year simulation which was 23% less than the net deposition value observed in the "without dredging scenario". In this scenario, the total sedimentation and erosion volumes were 509,702 m^3 and -189,136 m^3, respectively, which were 22% and 21% less than the corresponding values in the "without dredging scenario". The trend of higher sediment volumes at the beginning of the examined area and higher erosion volumes at the end of the area continued in this simulation also. Additionally, the analysis indicated that the highest sedimentation rate occurred at c.s. 52, with approximately 40,000 m^3, which was 35% less than its corresponding value in the "without dredging scenario". On the other hand, c.s. 91 had the largest amount of erosion, with around -30,000 m^3, which was 16% less than its corresponding value in the "without dredging scenario".

After the 20-year simulation, the "with dredging scenario" also showed a trend towards deposition, with a net deposition of 392,242 m^3. This value was 26% less than the net deposition observed in the "without dredging scenario" for the same simulation period of 20-year. The total sedimentation and erosion volumes in this scenario were 611,086 m^3 and -218,844 m^3, respectively, representing a 27% and 28% decrease compared to the "without dredging scenario". Similar to the "without dredging scenario", higher sediment volumes were observed at the beginning of the study area, while erosion rates were greater towards the end. C.s. 52 had the highest sedimentation rate, with approximately 48,500 m^3, which was 27% less than its corresponding value in the "without dredging scenario". C.s. 91 experienced the largest amount of erosion, with around -30,000 m^3, which was 29% less than its corresponding value in the "without dredging scenario".

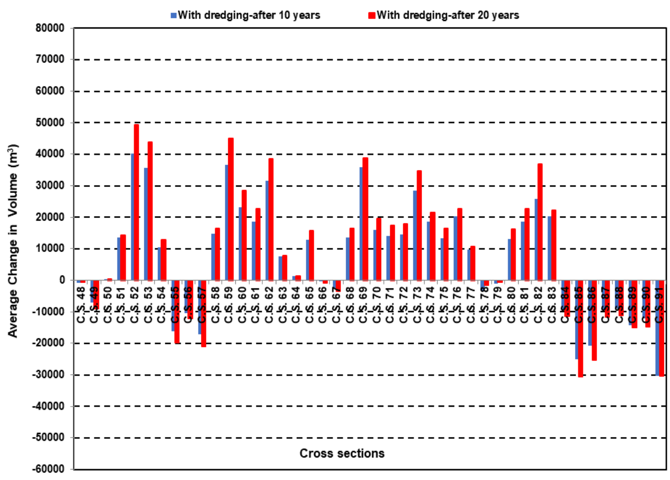

Figure 21. Average volume change of sedimentation and erosion at the 44-cross sections DS Beni-Suef bridge in case of with dredging scenario.

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The analysis revealed also that, under the non-dredging scenario, approximately 79% of the total net sediment deposition over the 20-year simulation period occurred within the first initial 10 years. Similarly, in the dredging scenario, around 82% of the cumulative net sediment volume was deposited during the first decade. These outcomes confirm the predominance of depositional processes, particularly in the first decade, and suggest a gradual transition toward morphodynamic equilibrium thereafter.

VIII. CONCLUSIONS

The construction of the Beni-Suef bridge has altered the natural flow regime of the Nile River, leading to significant morphological transformations downstream of the structure. To assess and predict these alterations, a one-dimensional HEC-RAS model was applied to a 2.6 km segment downstream of the bridge. The model incorporated three sediment transport formulas: Ackers-White, England-Hansen, and Yang for calibration and validation purposes. Morphological simulations were conducted over 10- and 20-years under both dredging and non-dredging scenarios.

Among the tested sediment transport formulas, the Ackers-White equation exhibited the highest accuracy, with marginal deviations of 1.5% in deposition and 1.1% in erosion if compared with observed values. The analysis revealed that sediment deposition was most prominent at the upstream boundary of the study area in both scenarios.

Under non-dredging conditions, the net sedimentation volumes reached approximately 416,915 m^3 after 10 years and increased to 529,125 m^3 after 20 years, representing a 27% rise. In comparison, scenarios incorporating dredging showed reduced sediment volumes of 320,566 m^3 and 392,242 m^3 over the same periods. Notably, for both scenarios, around 80.5% of the total deposition occurred in the first decade, indicating dominant early-stage deposition and a gradual shift toward morphodynamic equilibrium.

Additionally, dredging operations were found to reduce sedimentation rates by 23% and 26% over the 10- and 20-year intervals, respectively. These findings affirm the effectiveness of dredging as a mitigation strategy and provide valuable guidance for future sediment management and navigational planning.

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