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Long-term hydro-morphological changes in rivers: a case study

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ABSTRACT

Over time, river hydro-morphological changes cause net aggradation or degradation in bed cross-sections. The presence of sediments in the flowing water as suspended or bed loads, as well as modifications to flow characteristics like velocity and discharge, are the main causes of these alterations. This study examined long-term hydro-morphological changes over 21 years (1982–2003) in the third Egyptian Nile River reach using bathymetric and hydrological data together with numerical simulation. The aims were to track the hydro-morphological changes, including aggradation and degradation, check the ability of HEC-RAS to determine the water surface profile, and check sections of different zones for navigation. It was found that most of the reach under study suffered degradation in the 21–year study period, with net volumes ranging between 8 and 779 m^3/m; the water surface profile calculated using HEC-RAS matched well with the measured one, the zone located between km 526 and km 534 changed from safe to unsafe for navigation, and the zone located between km 397 and km 385 changed from unsafe to safe for navigation.

Key words: HEC-RAS, hydro-morphological changes, Nile river, safety for navigation, third reach, water surface profile

HIGHLIGHTS

- Bathymetric survey data were used to track hydro-morphological changes with time.
- Most of the cross-sections were found to suffer degradation.
- HEC-RAS software was proven to be efficient in determining the water surface profiles.
- Navigation safety is studied via utilizing configurations of the river cross-sections and water levels.

1. INTRODUCTION

The Nile, one of the world's longest rivers, flows through 10 distinct countries in eastern Africa. The Egyptian Nile River (ENR) refers to the last 1,200 km of the 6,800-km-long Nile River that is contained within the Egyptian borders between the High Aswan Dam (HAD) and the Mediterranean Sea. For various river cross-sections, sediment movements combined with water flow cause aggradation or degradation. The construction of the HAD near the southern Egyptian borders seized sediments from flowing from the Ethiopian plateau to Egypt.

Aggradation and degradation with time are among the main factors determining the water surface profiles, inundation associated with flood events, safety of navigation through the river, etc.

Long-term hydro-morphological studies are important for the ENR as it experienced many mega changes through its recent history, from aggradation by the seasonal flood to the degradation just after constructing the HAD to finally a hesitated state where the changes in discharge and velocity, from one section to another along ENR, play a very important role in degradation and aggradation.

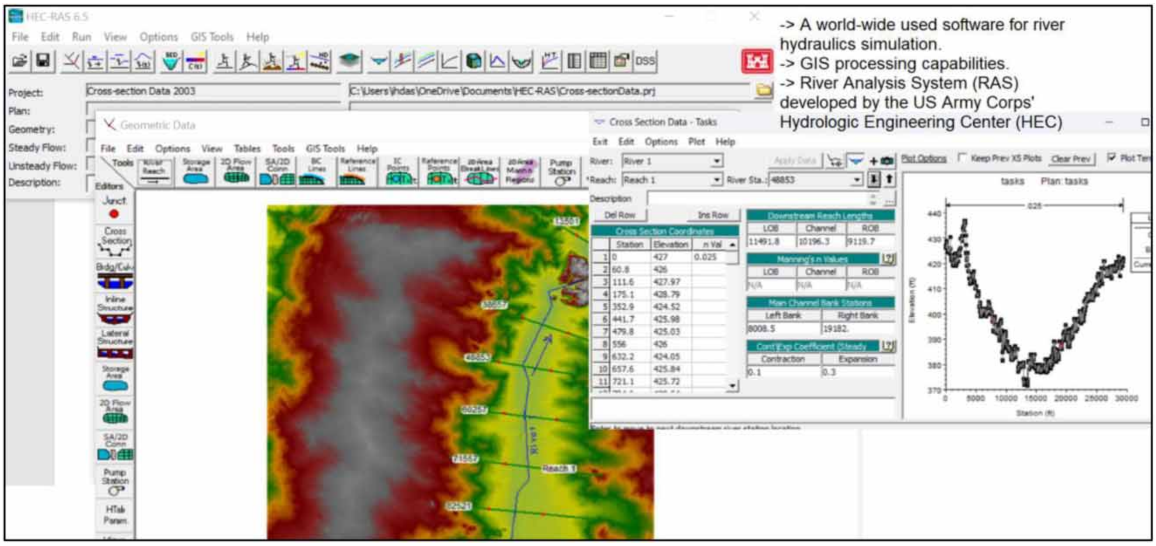
In the literature, one may find that many attempts were made to study the hydro-morphological conditions of rivers using different techniques such as comparing historical bathymetric survey, satellite image processing, and modeling using hydrodynamic software as will be briefed hereafter.

Kristensen *et al.* (2014) evaluated the long-term (10 years) hydrological effects of the restoration of the lower river Skjern (Denmark). They monitored how stream ecosystems were changing, how sediment movement was altering the river's cross-section profile, and how river restoration was re-establishing the relationship with floodplains. To assess the causes and consequences of hydro-morphological changes in the Iberian Minho River, Kuriqi *et al.* (2017) employed a planform change study. They conducted a chronological comparison of numerous hydro-morphological features using old maps. The study found that the area of lentic habitats had decreased, which resulted in a shift in fish habitat and a drop in the width of the active stream. Hajdukiewicz & Wyżga (2019) used historical aerial photographs to track a mountain river's hydro-morphological changes over the previous 60 years. They demonstrated how river communities are negatively impacted by the deteriorated hydro-morphological conditions. The Hydro-morphological Index for Rivers approach was established in 2017, and studies by Szoszkiewicz *et al.* (2020) and Tomczyk *et al.* (2021) demonstrated its usefulness in identifying substantially changed water bodies when utilized within the context of Geographic Information System (GIS). By contrasting two neighboring sections, one shaded by trees and the other not, Kałuża *et al.* (2020) emphasized the impacts of shadowing by trees and shrubs on the hydro-morphological alterations of the Wełna River, Poland. Their approach primarily relied on using historical aerial photographs to track a mountain river's hydro-morphological changes over the previous 60 years. To evaluate the influence of a constructed hydropower plant, Tomczyk *et al.* (2021) examined the hydro-morphological conditions of river cross-sections upstream (US) and downstream (DS). Del Tánago *et al.* (2021) examined the significance of riparian vegetation for river hydro-morphology, emphasizing how it affects sediment regime conditions and streamflow. The Mahananda–Balason River system in West Bengal, India, was evaluated for hydro-morphological quality by Mitra *et al.* (2022) using the multiparameter-based Hydro-morphological Quality Index. They claimed that their approach was appropriate for ongoing river system monitoring. The European Union's claim that small hydropower plants with less than 10 MW have no impact on rivers was refuted by Stanca *et al.* (2023). They discovered that modest hydropower plants affect the primary hydro-morphological parameters and suggested a methodology based on linear interpolation. Moldoveanu *et al.* (2023) evaluated the cumulative hydro-morphological consequences by using real-world examples of two rivers and the drivers-pressures-state-impacts-responses (DPSIR) framework. Seidl *et al.* (2023) combined various GIS methods, pebble counts, and simulation with HEC-RAS to track the Katun River's large-scale hydro-morphological features. The hydro-morphological characteristics of rivers are accurately simulated by the HEC-RAS software in both steady and irregular flow scenarios.

In this study, the hydro-morphological changes in the ENR concerning bed configurations and water surface profile are being investigated. The study's findings will then be used to assess the safety of navigation in the third reach of the ENR. This research employs the methodology of Kristensen *et al.* (2014), Kuriqi *et al.* (2017), Hauer *et al.* (2021), and Seidl *et al.* (2023) to track hydro-morphological changes using historical bathymetric maps. In addition, it adheres to the advice of using the HEC-RAS as a one-dimensional step-backwater modeling software for tracking river hydro-morphological features in both unsteady-state and steady-state modeling (Cook 2008; Hauer *et al.* 2013, 2016, 2021; Zhonglong & Billy 2014; Xafoulis *et al.* 2022; Alemu *et al.* 2023). It is intended to provide water engineers, particularly those who work with the Nile River, with fresh perspectives.

HEC-RAS stands for the software production of the U.S. Army Corps of Engineers Hydrologic Engineering Center, River Analysis System. As stated in the manual of the software (HEC-RAS User's Manual n.d.), the HEC-RAS modeling system was developed as a part of the Hydrologic Engineering Center's 'Next Generation' (NexGen) of hydrologic engineering software. This NexGen production included software for reservoir system simulation (HEC-ResSim), rainfall-runoff analysis (HEC-HMS), flood damage analysis (HEC-FDA), river hydraulics (HEC-RAS), and others. The software has many modules that allows the user to perform many applications regarding different flow aspects in rivers and other open channel streams. Figure 1 shows some interfaces of the software and part of its uses and abilities such as modeling of steady flow analysis in open channels.

HEC-RAS was intensively used to monitor the hydro-morphological variations of rivers. Zhonglong & Billy (2014) introduced a technical note from the Ecosystem Management and Restoration Research Program (EMRRP) aiming at documenting the application and evaluation study of the Hydrologic Engineering Center-River Analysis System-Nutrient Simulation Module I (HEC-RAS-NSM I) model for the Lower Minnesota River. They reported that their model was adopted from QUAL2E and CEQUAL-RIV1 software. Hauer *et al.* (2021) integrated satellite imagery and hydrodynamic HEC-RAS to monitor different landscape units of the Vjosa river in Albania, such as the active river stream channel, river floodplain, and morphological floodplain. Xafoulis *et al.* (2022) created flood inundation and flood hazard maps of river streams using GIS software, the unsteady 2D HEC-RAS model that solved the 2D Saint-Venant equations, and hydrographs based on the rainfall data that were available during the flood occurrence period. Comparing their model with field data, it was proved


-> A world-wide used software for river hydraulics simulation.
-> GIS processing capabilities.
-> River Analysis System (RAS) developed by the US Army Corps' Hydrologic Engineering Center (HEC)

Project: Cross-section Data 2003 C:\Users\hdas\OneDrive\Documents\HEC-RAS\Cross-sectionData.prj

River: River 1

Reach: Reach 1 River Sta.: 48853

Cross Section Coordinates

	Station	Elevation	n Val
1	0	427	0.025
2	60.8	426	
3	111.6	427.97	
4	175.1	428.79	
5	352.9	424.52	
6	441.7	425.98	
7	479.8	425.03	
8	556	426	
9	632.2	424.05	
10	657.6	425.84	
11	721.1	425.72	

Downstream Reach Lengths

LOB	Channel	ROB
11491.8	10196.3	9119.7

Manning's n Values

LOB	Channel	ROB
N/A	N/A	N/A

Main Channel Bank Stations

Left Bank	Right Bank
8008.5	19182.

Cont\Exp Coefficient (Steady)

Contraction	Expansion
0.1	0.3

Figure 1 | Applications and abilities of HEC-RAS (data shown are from one of the preliminary training runs).

to be reliable. The enhanced usefulness of citizen science data in flood modeling research was examined by Alemu *et al.* (2023) in Addis Ababa, Ethiopia, monitoring river levels at specific locations along the main course of the Big Akaki River during floods. They forced a one-dimensional HEC-RAS flood model to operate using the collected data and assessed its sensitivity to various inputs and parameter values. The simulated water level varied significantly when the DS boundary condition was changed.

2. PROBLEM DEFINITION AND STUDY AREA

The ENR has two parts. The first part has one stream situated between the HAD and the Delta Barrage, north of Cairo, the capital of Egypt. The second part is the Nile delta, where the Nile splits into two branches, expanding northward and reaching the shore of the Mediterranean Sea at Rosetta city western wise and Damietta city eastern wise.

Up to the Egyptian Ministry of Water Resources and Irrigation (MWRI), the first part of the ENR is divided into four reaches (see Figure 2): *Reach I* is extended from DS of HAD (km 0) to US of Esna barrage (km 166.65); *Reach II*: from DS of Esna barrage to US of Nag Hammadi barrage (km 359.54); *Reach III*: from DS of Nag Hammadi barrage to US of Assiut barrage (km 544.75); *Reach IV*: from DS of Assiut barrage to US of Delta barrage (km 953). Even though the time of the flood season of the Nile River is well known, the discharge of the flood suffers dramatic variations over the flood years. It is useful here to report that the discharges recorded at the Dongla gauging station in Sudan ranged from 150 km^3/year (in 1878) to 43 km^3/year (in 1913). However, the discharges released from HAD vary according to the changes in flood discharges and seasonal Egyptian water demands.

The discharge variations, the human encroachment, and the climatic changes make it necessary for Egyptian engineers and researchers to study the continuous hydro-morphological variations of the ENR, including changes in water and bed levels and the stream width due to silting and scouring. These changes impact the intakes of drinking water, hydroelectric power stations, navigation, stability of side slopes, overtopping of banks, and the like. This study investigates the hydro-morphological variations of Reach III of the ENR.

The third reach of ENR, which is 185.21 km long and situated between the Assiut and Nag Hammadi barrages, is the focus of this study. This involved nearly 14 million people living in the three upper Egyptian governorates of Qena, Sohag, and Assiut. The Nile valley is extremely small, with an average width of less than 10 km, and the Nile stream is almost straight in this reach. The valley is surrounded by hundreds of kilometers of the eastern and western deserts of Egypt; hence, sandstorms and desertification affect agricultural areas. The study benefited from the existence of 17 Nile gauge stations located across the reach, ranging from the DS of the Nag Hammadi barrage station down to the US of the Assiut barrage station. While some of these stations merely record the actual surface water level, others record the actual discharge in addition to the surface water level.

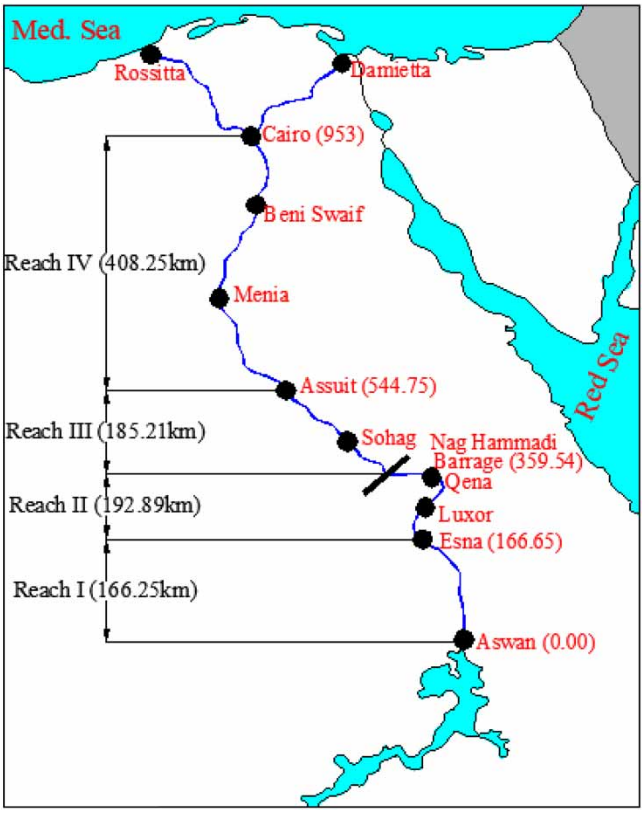


Figure 2 | Reaches of the ENR.

3. MATERIALS AND METHODS

This study was carried out using numerical approaches and field data sampling. Hydrological and geomorphological data for the third reach of ENR were included in the field data. HEC-RAS software was used in the numerical study, and the outcomes were compared to field data.

3.1. Hydrological data

As mentioned earlier, this study benefited from the existence of 17 Nile gauge stations distributed along the length of the reach under study. These gauge stations are Naga Hammadi Barrage, Naga Hammadi weir, Geziret Eldom, Elsheikh Mebader, Elawameer, Aboshosha, Elbalina, Ras Fakhry, Girga, Sohag, Elkormata, Elmaragha, Elkhezindaria, Megris, Elmatar, Aboteeg, and Assiut barrage located at km 359.50, 359.50, 362.2, 366.85, 373.00, 379.90, 386.60, 398.00, 405.10, 445.95, 457.55, 470.00, 479.10, 509.50, 518.00, 520.50, and 544.75 from the HAD, respectively. The hydrologic data included the discharges and the water levels. The discharges varied from 520 to 4,050 m^3/s, while water levels varied from 48 to 61.5 m.

The discharges that HAD authority allowed one to pass in the reach under study are used to identify four scenarios per study period. For the year 1982, the scenarios of 1,150, 1,500, 1,800, and 2,000 m^3/s were chosen, while for the year 2003, the scenarios of 520, 1,500, 1,800, and 2,000 m^3/s were chosen. These scenarios were selected considering the availability of the hydrologic data at the previously indicated stations. Hydrological data were used to verify the results and calculations of the software.

3.2. Geomorphological data

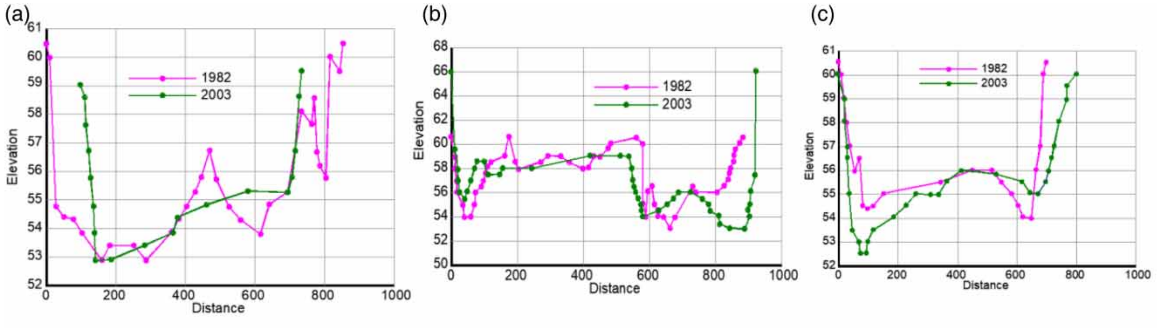
Geomorphological changes (bed elevation) for Reach III in the ENR were tracked from 1982 to 2003 using bathymetric and land surveys. Elevations with respect to the mean sea level were sampled for the reach under study and loaded in GIS tools ArcMap and SURFER to develop cross-sections and compute cut and fill. Comparing the cross-sections of the same station from 1982 to 2003 allowed the determination of whether erosion or sedimentation existed in the cross-sections of the reach under study.

4. ANALYSIS AND DISCUSSION

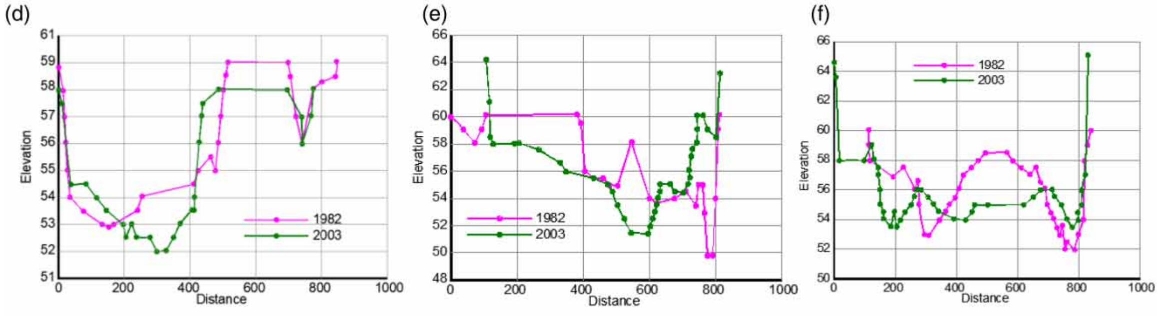
4.1. Aggradation and degradation in bed elevations

Aggradation and degradation are two of the key processes that dictate most of the hydro-morphological features of rivers. These are fluvial processes that are typically impacted by sediment load, river discharge, human interventions, and the morphology of river channels (Mugade & Sapkale 2015). Aggradation occurs when the input sediment discharge in a given cross-section of the river channel exceeds the discharge carrying capacity, and vice versa.

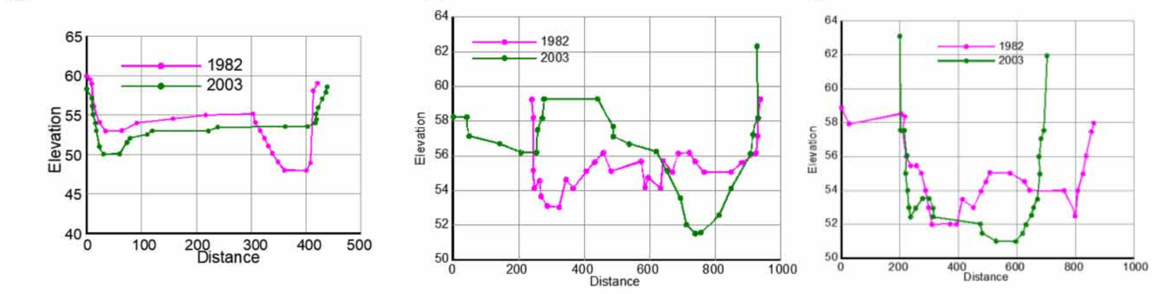
Pairs of bed layouts at various cross-sections of the ENR in the reach under study are shown in Figure 3(a)–3(i). The riverbed's widths range from 440 to 830 m. Because of the sediment transport and other hydraulic processes, the elevations of the various cross-sections differ significantly. In the same section, no trends are observed. That is, the same cross-section in every figure shows signs of aggradation and degradation. The figures and Table 1 demonstrate how some cross-sections' widths, such as those at km 374 and 418, drastically shrank over time. Section widths were somewhat widened in a few more instances, as shown in the occurrences at km 382 and 414. The widths stayed roughly the same in the remaining river cross-sections.



Km 374 Km 378 Km 382



Km 390 Km 394 Km 398



Km 410 Km 414 Km 418

Figure 3 | Bed configurations at the cross-sections in the Nile River in the years 1982 and 2003.

For each cross-section, the net aggradation or degradation was computed. Table 1 shows the value of the volume altered per unit length as well as whether the cross-section suffers aggradation or degradation. Table 1 demonstrated that most cross-sections experienced degradation. Only two cross-sections exhibited aggradation:

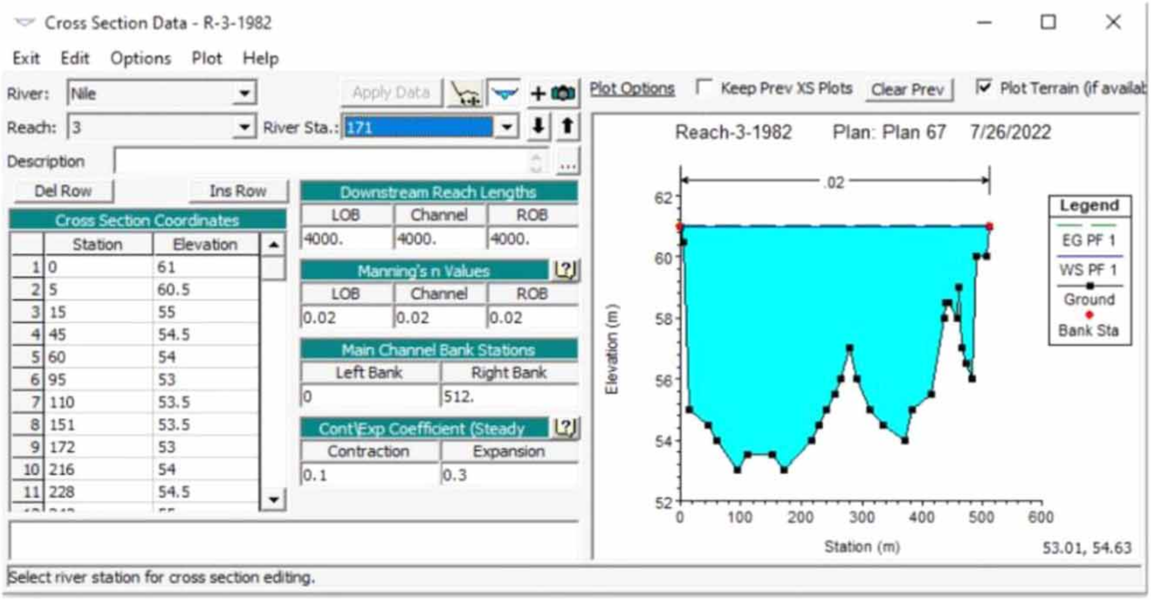
Table 1 | Aggregation and degradation volumes at different sections

Section at km	Aggradation/degradation	Volume/unit length (m^3/m)	Section width
374	Aggradation	172	Decreased
378	Degradation	567	Approximately the same
382	Degradation	425	Increased
390	Degradation	517	Approximately the same
394	Degradation	779	Approximately the same
398	Degradation	200	Approximately the same
410	Degradation	8	Approximately the same
414	Aggradation	206	Increased
418	Degradation	232	Decreased

km 414 by 206 m^3/m and km 374 by 172 m^3/m. The sediments were lost from all other cross-sections with quantities that vary from 8 m^3/m at km 410 to 779 m^3/m at km 394. It should be noted that the net sediment moved out or into a cross-section does not necessarily match the section's increasing or decreasing bed width. For instance, during the study period of 1982–2003, the cross-section at km 418 suffered degradation (net sediments were moved out of the section), while its width was reduced. This could be because sediment moves in and out of the section in an uneven manner over the bed width.

4.2. Water surface profile

First, four scenarios were chosen per study year. Second, water elevations in the two years at the set sections, under various discharge scenarios, were calculated by the HEC-RAS software. Third, measured and calculated water surface profiles were compared. Figure 4 displays the results of the software and data input in the year 1982, with a discharge of 1,800 m^3/s at km 374 from HAD as an example. Table 2 shows the tabulated data input and simulation results in HEC-RAS in the year 1982 (Q = 1800 m^3/s).



River: Nile

Reach: 3 River Sta.: 171

Description

☐ Keep Prev XS Plots

☑ Plot Terrain (if availab

Cross Section Coordinates

	Station	Elevation
1	0	61
2	5	60.5
3	15	55
4	45	54.5
5	60	54
6	95	53
7	110	53.5
8	151	53.5
9	172	53
10	216	54
11	228	54.5

Downstream Reach Lengths

LOB	Channel	ROB
4000.	4000.	4000.

Manning's n Values

LOB	Channel	ROB
0.02	0.02	0.02

Main Channel Bank Stations

Left Bank	Right Bank
0	512.

Cont\Exp Coefficient (Steady

Contraction	Expansion
0.1	0.3

Select river station for cross section editing.

Figure 4 | Data input and simulation results in HEC-RAS in the year 1982 (*Q* = 1,800 m^3/s).

Figures showing the relations between water surface profiles and the discharges in the Nile River are of great importance as these relations have been used for centuries to give information to engineers. Old Egyptians built scales for water levels to determine the Nile water levels and consequently the Nile discharges. In this study, the

Table 2 | Tabulated data input and simulation results in HEC-RAS in the year 1982 ($Q = 1{,}800\ \mathrm{m}^3/\mathrm{s}$)

Station	Elevation
0	61
5	60.5
15	55
60	54.5
95	54
110	53
151	53.5
172	53.5
216	53
228	54.5
330	54
345	54.6
360	55
380	55.6
390	56
420	57
435	56
465	55
510	54.5
560	54
570	55
625	55.6
660	58.4
665	58.4
690	58
692	59
695	57
730	56
740	60
760	60
763	61

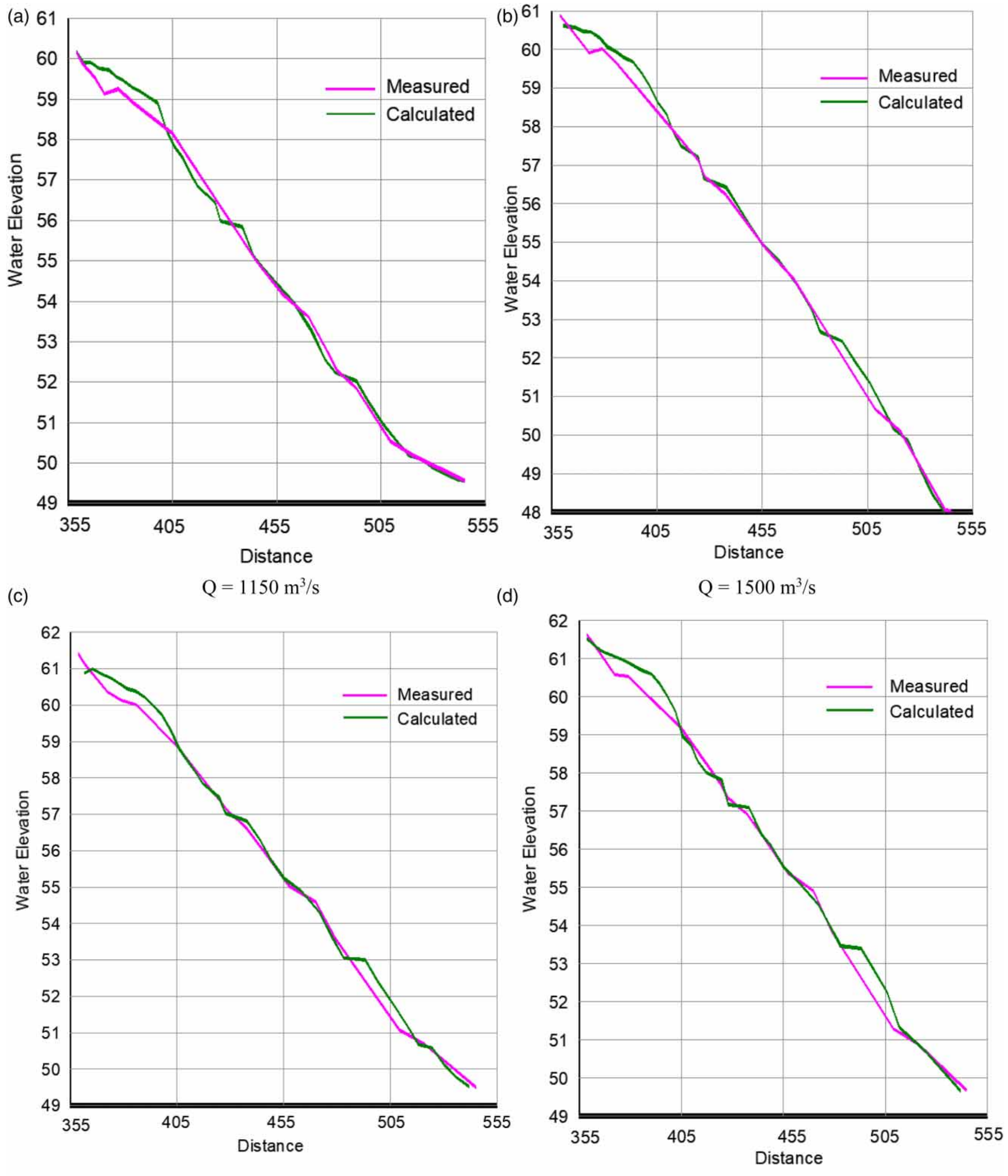
goal of setting and analyzing these figures is to check the calculated results of the HEC-RAS software with the actual measured data.

Figures 5(a)–5(d) and 6(a)–6(d) show the water surface profiles of the four scenarios of the years 1982 and 2003, respectively. In these figures, the green curves represent the results of the HEC-RAS software, while the magenta curves give the actual measured data. Comparing the eight pairs of curves in the eight figures cleared that the HEC-RAS could accurately determine the water surface profile for the ENR in the reach under study in different scenarios. That is numerical data matched well with the measured data. Based on this result, HEC-RAS was used to conduct more calculations for the study reach as will be shown hereafter.

4.3. Safe navigation through the study reach

ENR has long been used as a route for trade goods along Egypt, along with the establishment of resorts and floating hotels for tourists. That is an extra or added economic value to the river's numerous other economic values.

The flow depth tends to increase as a result of the degradation process, enhancing navigation safety. Safe navigation along the reach is not guaranteed, even though it was discovered in Section 4.1 that most of the reach had



Q = 1150 m^3/s

Q = 1500 m^3/s

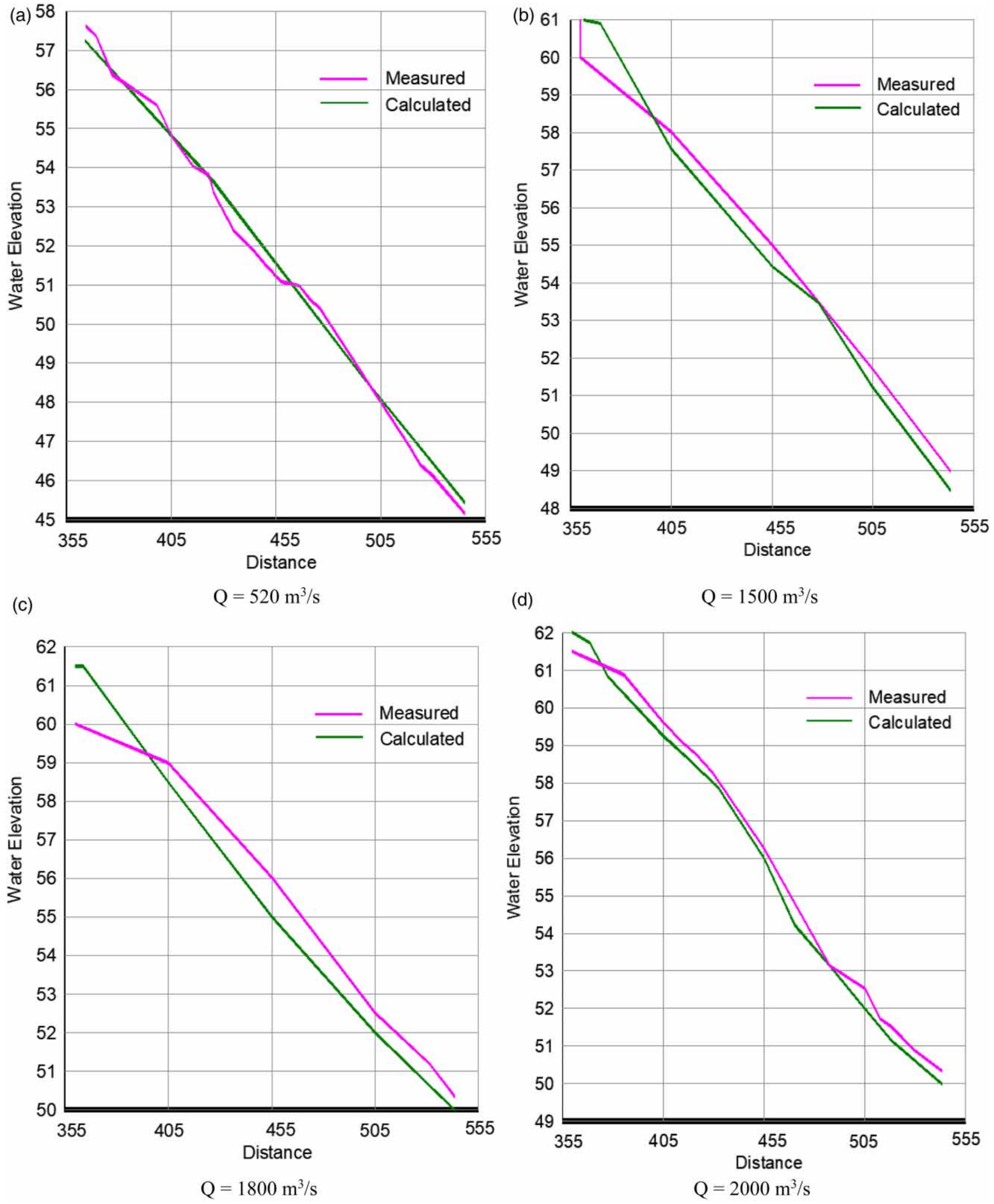
Q = 1800 m^3/s

Q = 2000 m^3/s

Figure 5 | Measured versus HEC-RAS calculated data for water surface profiles for scenarios of 1982.

experienced net degradation. This is because the net degradation is not distributed equally along the bed width in the cross-sections, creating hazardous navigation situations if degradation does not occur at all along the bed width needed for navigation (refer to Figure 3 and Table 1).

The minimum dimensions for the ENR cross-section for safe navigation, as stated by Abdel-Aziz 2004 and adopted by the Egyptian MWRI, are affected by the dimensions and average velocity of the barges commonly used through the ENR, together with the prevailing wind intensity. He mentioned that the cross-section should guarantee a waterway of at least 100 m bottom width, 2.3 m water depth, and side slopes of 5:1 giving a 123 m top width. These limitations were adopted in this study and fed to HEC-RAS software to point out the sections of safe and unsafe navigation for the minimum discharge case in 1982 and 2003 ($Q = 520\ m^3/s$) as examples of severe navigation flow conditions.



$Q = 520\ m^3/s$

$Q = 1500\ m^3/s$

$Q = 1800\ m^3/s$

$Q = 2000\ m^3/s$

Figure 6 | Measured versus HEC-RAS calculated data for water surface profiles for scenarios of 2003.

The software results for the study years 1982 and 2003 are displayed in Figure 7(a) and 7(b), where the locations of the parts that are safe and unsafe for navigation along the study area are indicated in green and red, respectively. Comparing the two figures, it was found that some parts of the reach changed from safe to unsafe for navigation such as in the zone located between km 526 and km 534, some parts of the reach changed from unsafe to safe for navigation such as in zone located between km 397 and km 385, and other parts remain the same.

Two illustrations of the unsafe and safe navigation sections are shown in Figure 7(c) and 7(d). The first example is an unsafe section located at km 530 from HAD (year 1982). Although the maximum water depth of the section was found 6.2 m (more than the required 2.3 m), the section is not safe for navigation as the required width with

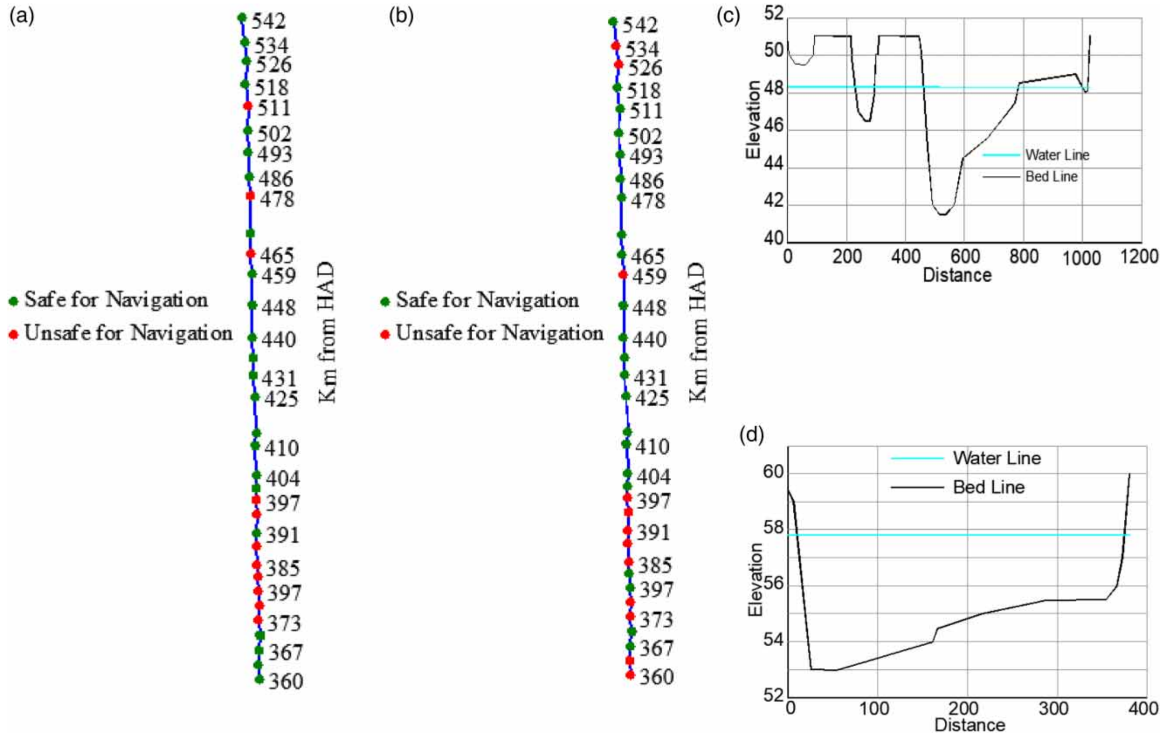


Figure 7 | (a) Safety for navigation (year 1982, $Q = 520$ m^3/s). (b) Safety for navigation (year 2003, $Q = 520$ m^3/s). (c) Section unsafe for navigation km 530 (year 1982, $Q = 520$ m^3/s). (d) Section safe for navigation km 553 (year 2003, $Q = 520$ m^3/s).

the minimum water depth does not exist. The second example is a safe section located at km 553 from HAD (year 2003). It has a safe bed width (where water depth is more than 2.3 m) of 270 m and a top width of 365 m. To maintain navigation all along the reach in case of minimum discharge, engineering measures of dredging with refining and even lining should be taken to maintain the cross-sections with the navigation allowable terms.

5. CONCLUSIONS

A field and numerical study was conducted for the third reach of the ENR to achieve the following goals: (1) monitor the hydro-morphological changes during the period from 1982 to 2003, (2) verify the certainty of using HEC-RAS software in calculating the hydro-morphological characteristics of the river reach, and (3) determine the zones in the reach under study that are safe and unsafe for navigation.

The study revealed that most of the reach under study suffered degradation in the studied 21 years (from 1982 to 2003), with net volumes ranging between 8 and 779 m^3/m. The HEC-RAS software proved to be an efficient tool for conducting the required hydro-morphological calculations with good accuracy. Figures with calculated and measured water surface profiles show the ability of HEC-RAS in the determination of the water surface profile with acceptable accuracy. Regarding safety for navigation and due to continuous hydro-morphological changes, some zones of the reach under study changed from safe to unsafe and vice versa. This is clear in the zone located between km 526 and km 534 changed from safe to unsafe for navigation and the zone located between km 397 and km 385 changed from unsafe to safe for navigation. The study proved the significance of carrying out regular measurements and calculations for the river streams to monitor the hydro-morphological variations.

ACKNOWLEDGEMENT

Sincere help of Y. Kamal during data sampling is highly appreciated.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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