Rosetta Branch conveyance capacity and rehabilitation scenarios

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Abstract

River networks are considered as conduits of variable conveyance flow from an engineering perspective. Alluvial channel networks alter their planform, and extent over time. The main objective of the research is to estimate the maximum conveyance capacity of the Rosetta branch of the Nile River in Egypt. A two-dimensional numerical model was used to evaluate the morphological and hydrological changes that occurred during a period of 17 years from the year 2003 to 2020 in the branch using different flow scenarios. The results show a prevailing deposition trend along the branch leading to a reduction in the maximum conveyance capacity. Three rehabilitation scenarios were proposed to increase the maximum conveyance capacity. Each scenario was evaluated by assessing its impact on the conveyance capacity, surface water elevation, and inundated land area. The proposed rehabilitation scenarios increased the maximum conveyance capacity and reduced inundated land area, but lowered the surface water elevation.

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Introduction

Practically all rivers are subject to morphological changes due to the dynamics of flow and sediment transport (Matsuda 2004). Alluvial rivers experience a frequent alteration in planform and cross-section due to the simultaneous sedimentation and erosion processes (Church 2006). River morphology and hydrology are recognized as essential elements for integrative studies that seek to develop an understanding of river behaviour to boost river management scenarios (Sear et al. 1995).

The stability of a river channel over a certain period is controlled primarily by the flow and sediment regimes. If any of these driving factors experience a sudden or a prolonged change, the river channel responds by changing its morphology (Pollock et al. 2014). Alluvial river channels frequently display a three-dimensional morphodynamic alteration in the aspects of river channel planform. The morphology of an alluvial river channel is the consequence of deposition and erosion processes in the river. Morphological changes are affected mainly by the amount and calibre of the sediment passing through the channel. Alluvial river channels are formed due to the transported and deposited sediments passing through the channel. Accordingly, the channel is self-formed (Church 2006).

The Nile River is the main source of water in Egypt. Nile River is known for its morphological changes related to alterations in the water flow regime (Farag et al. 2021). The Nile River travels 927 km from Aswan High Dam (AHD) till it reaches Nile Delta afterward it emerges into two branches; the Damietta branch towards the east and the Rosetta branch towards the west. Rosetta branch is approximately 240 km in length starting from Delta Barrage till it reaches its promontory on the Mediterranean Sea.

The flow in the Nile River is controlled by (AHD) southern Egypt. (AHD) construction on the Nile River in the year 1964 altered the flow and sediment regime along the Nile River. The most common effect of dams is flattening the hydrograph curve of the flow passing through the downstream. Sediment transport is also affected as large amounts of sediment are trapped, releasing only a fragment of the trapped load into the river channel. Flow discharge passing through the Rosetta branch before AHD construction could reach 600 million m3/day, and about 220 million m3/day after AHD construction. Suspended sediment load concentration at El Gafaraa gauge Station on Nile River downstream the AHD decreased from 3800 ppm before the construction of the dam to 50 ppm after the dam construction as the total sediment load was decreased by a percentage of 98% (Shalash 1980).

Conveyance capacity is described as the ability of a river channel to convey a specified flow of water (Venczel 2008). Maximum conveyance capacity is the amount of flow that a channel can convey before overtopping. Flow conveyance is the discharge conveyed through a given channel segment for a given stage. Modifications to the channel geometry or factors affecting the water velocity will modify how flow is conveyed through the channel. An important challenge in estimating conveyance capacity is how to account for the complexities of real rivers taking into account their shape, depth, length, sinuosity, meandering, and roughness, and the capability to represent them in numerical models (Samuels et al. 2002).

(Venczel 2008) declared that the main type of factors affecting river conveyance capacity is “Instream factors”. The “Instream factors” refer to direct changes to the channel planform that affect the conveyance capacity of a river. These instream changes can be summarized as follows; Revetment structures, channel shape, flow velocity, meander cut-offs, dredging operations, locks, dams, levees, and human encroachment.

Efforts to restore the conveyance capacity and flow regime of rivers across the world have caught huge attention due to the remarkable morphodynamic changes in natural channels. Dredging operations are the removal of the topsoil from the river bed. Dredging operations are considered a solution to increase the conveyance capacity of any river by offering a direct impact on river conveyance capacity in a short duration as the results are immediate but also has many disadvantages as it is considered a temporary solution demanding frequent dredging operations, lowering the surface water profile, and have a high operations cost.

Numerical modeling is essential in evaluating river morphological changes. The conveyance capacity of the western branch at Warrak island in the River Nile, Egypt was investigated in a study by (Salama et al. 2020) using a two-dimensional numerical model. The study evaluated current conveyance capacity and proposed various scenarios to increase the flow conveyance of the study area mainly depending on dredging operations and removing the unmanaged human intervention at the island. Their study showed that dredging to a safe navigation elevation increased the conveyance capacity of the western branch of the island from 31.4% to 45.5%. (Enas 2021) used a two-dimensional numerical model to assess dredging operations’ impact on navigability of the second reach of the Nile River. Results revealed that dredging operations alone cannot be adopted as a permanent solution for river navigation bottlenecks as the riverbed returns to its original form within 10 years. (Magdy 2021) also used a two-dimensional numerical model to assess dredging operations as a solution for some navigation bottlenecks in the third reach of the Nile River with results proving that dredging can be a suitable solution.

The main objective of this study is to estimate the maximum conveyance capacity of the Rosetta branch. Analyze morphological changes that occurred during a period of 17 years starting from the year 2003 to 2020 using a two-dimensional numerical model, conducting hydrological and inundated land analysis, proposing three rehabilitation scenarios to increase Rosetta branch maximum conveyance capacity, and assessing each scenario's impact on surface water profile, stream velocity, and inundated lands related to different flow discharge scenarios.

Materials and method

The methodology approach mentioned in this study consists of four stages. The first stage is data collection of hydrographic data, hydrological records, bed material samples, and velocity measurements. The second stage is model preparation by mesh generation, model calibration, and verification using boundary conditions. The third stage is a model application to evaluate the morphological, hydrological changes, flooded land analysis, the current maximum conveyance capacity of the Rosetta branch. The fourth stage is the results and analysis of the three proposed rehabilitation scenarios' impact on water surface profile, inundated land, and conveyance capacity as shown in Figure 1.

Study area

The study area covers approximately 155 km in the Rosetta branch of the Nile River in Egypt. Extending from Delta Barrage at Km 26 heading north reaching Shabrakhet gauge station at Km 181 downstream Elroda gauge station. Rosetta branch is considered a meandering channel whose sinuosity index is 1.5 and average channel width 122 m. The study area includes five water gauge stations and one control structure in addition to 5 drains discharging its effluent directly into the branch as shown in Figure 2.

Data collection

Hydrological data

Daily water level records of five water gauge stations (Elkhatatba, Abo Elkhawey, Zaywet Elbahr, Kafr Elzayat, and Shabrakhet) and flow discharge records of Delta Barrage were collected for the study. The average daily discharge of five drains (Elrahawey, Sabl, Eltahrer, Zawyet Elbahr, and Tala) was also collected. The collected data have a return period of 15 years from 2005 to 2020. The collected data revealed that the maximum flow discharge values are mainly recorded from June to August, while the minimum values are from November to January. The maximum recorded discharge was about 90 million m3/day during the year 2007, while the minimum discharge was 5 million.m3/day during the year 2005.

Hydrographic data

The hydrographic data consists of a Hydrographic survey of the study area bed level with a length of 155 km during the years 2020 and 2003. The hydrographic survey was carried out by the Nile Research Institute (NRI) of the National Water Research Center (NWRC) in Egypt.

Bed material samples and velocity measurements

Four velocities cross-sections were selected for model calibration and verification. The streamflow velocity was measured in the field. The first two were at km 37 while the second two were at km 140 from Elroda gauge. Also, five locations were chosen for bed material sample extraction at km (57,64,94,120, and 150) respectively from Elroda gauge where the average D_{50} was 0.35 mm and soil classification was fine to medium sand.

Numerical model

SRH-2D numerical model

The Sedimentation and River Hydraulics-Two-Dimensional model (SRH-2D) was implemented in this study. The SRH-2D is a module integrated into the surface water modeling system package (SMS-2D) which is a comprehensive package of tools for simplifying the development of 2D hydraulic models. (SRH-2D) is a 2D hydraulic numerical model based on 2D hydraulic principles for river hydraulics and sediment transport developed at the U.S. Bureau of Reclamation (USBR) (Aquaveo 2013). (SRH-2D) solves the time and depth-averaged Navier Stokes equations (known as the depth-averaged St.Venant Equations) to govern the flow regime (Lai and Greimann 2008) as follows:

$$\frac{\partial \mathbf{H}}{\partial \mathbf{t}} + \frac{\partial \mathbf{HU}}{\partial \mathbf{x}} + \frac{\partial \mathbf{hV}}{\partial \mathbf{y}} = 0 (1)$$

$$\frac{\partial \mathbf{HU}}{\partial \mathbf{t}} + \frac{\partial \mathbf{HUU}}{\partial \mathbf{x}} + \frac{\partial \mathbf{HVU}}{\partial \mathbf{y}} = \frac{\partial \mathbf{HT}_{\mathrm{xx}}}{\partial \mathbf{x}} + \frac{\partial \mathbf{HT}_{\mathrm{xy}}}{\partial \mathbf{y}} - \mathrm{gH}\,\frac{\partial \mathbf{z}}{\partial \mathbf{x}} - \frac{\tau_{\mathrm{bx}}}{\rho} (2)$$

$$\frac{\partial \mathbf{HV}}{\partial \mathbf{t}} + \frac{\partial \mathbf{HUV}}{\partial \mathbf{x}} + \frac{\partial \mathbf{HVV}}{\partial \mathbf{y}} = \frac{\partial \mathbf{HT}_{\mathrm{xy}}}{\partial \mathbf{x}} + \frac{\partial \mathbf{HT}_{\mathrm{yy}}}{\partial \mathbf{y}} - \mathrm{gH}\frac{\partial \mathbf{z}}{\partial \mathbf{y}} - \frac{\tau_{\mathrm{by}}}{\rho} (3)$$

where x and y: horizontal cartesian coordinates, t: time, H: water depth, U, V: depth-averaged velocity in x and y directions respectively, g: gravitational acceleration, $T_{??}$, $T_{??}$, $T_{??}$: depth-averaged stresses due to turbulence, $?_{??}$, $?_{??}$: bed shear stresses, ?: water density, $Z=Z_{?}$ + h, Z: water surface elevation, $Z_{?}$: bed elevation.

Mesh generation and boundary conditions

The generated mesh which represents the study area using the SRH-2D numerical model consists of a total number of 180,000 triangular elements with a minimum width of 30m. The bed level elevation was assigned to mesh elements at each node. The upstream boundary conditions are the flow discharge from the delta barrage and five drains. The downstream boundary condition is the water level at the Shabrakhet gauge station corresponding to the upstream flow as shown in Figure 3.

Model calibration and verification

The numerical model was calibrated using flow discharge of the year 2021 with the corresponding water level and stream velocity at two cross-sections as shown in Figure 4. The best suitable value for the manning roughness coefficient (n) is 0.015 after several model simulations. The numerical model was also verified using flow discharge of the year 2018 with the corresponding water level and stream velocity at two cross-sections as shown in Table 1. Model performance was verified by computing mean absolute deviation (MAD), mean square error (MSE), and root mean square error (RMSE) as shown in Figure 4(c).

Model application

After successfully calibrating and verifying the numerical model it will be implemented to achieve the following:

Evaluating morphological changes that occurred in the study area during 17 years between 2003 and 2020 by computing erosion and deposition volume and rate per year.

Assessing hydrological changes that occurred in the study area by computing differences in surface water elevation for different flow discharges passing through the Rosetta branch.

Calculating inundated land due to different flow discharges scenarios.

Estimating Rosetta branch maximum conveyance capacity.

Proposing and evaluating three rehabilitation scenarios to increase the Rosetta branch's maximum conveyance capacity.

Rehabilitation scenarios

Three rehabilitation scenarios were proposed for Rosetta Branch to increase the maximum conveyance capacity the branch can stream and reduce land inundation caused by high flow discharges as shown in Figure 5(a). The first scenario requires dredging a channel with a width of 40 m and depth of 2.3 m below minimum water surface elevation related to a minimum flow discharge of 5 million m^3/day along the thalweg line of the study area. The second scenario dredging channel depth is 3.5 m. The third scenario is similar to the first one but in addition to removing specified locations. These specified locations include under-forming islands, contraction points, flood plains, and shallow depth areas causing increased water levels and decreased conveyance capacity as shown in Figure 5(b).

Results and analysis

Rosetta branch conveyance capacity evaluation

The current maximum conveyance capacity of the Rosetta Branch is evaluated by integrating morphological, hydrological, and inundated land analysis. The morphological analysis shows a trend of deposition along the Rosetta branch by comparing bed elevation of the years 2003 and 2020. The calculated volume of deposition is about 12.6 million m^3 nearly double the erosion volume of 5.8 million m^3 .The maximum deposition annual rate is 0.22 m/year also nearly double the maximum erosion annual rate of 0.12 m/year as the average annual deposition and deposition rates are 3 and 2 cm/year respectively.

The rating curve of Rosetta Barrage during the years 1964 and 2018 shows an increase in water elevations due to the deposition trend in the branch as shown in Figure 6(a). Analysis of water surface elevations resulting from applying different flow scenarios ranging from 5 to 250 million m^3/day in the numerical model shows an increase in water elevation by an average range of (13-28) cm as shown in Figure 6(e). Analysis of inundated land area resulting from the same flow discharge scenarios shows an increase in flooded land by an average range of (12-200) % as shown in Figure 6(c).

Rosetta branch maximum conveyance capacity experienced a decrease by 25% between the year 2003 and 2020 as the maximum flow discharge that Rosetta Branch can convey without causing any land on the right or left bank to be inundated is 30 million m^3/day, whereas the maximum conveyance capacity of the year 2003 was about 40 million m^3/day.

Rehabilitation scenarios analysis

The three proposed scenarios were evaluated by integrating water surface elevation, stream velocity, inundated land, and maximum flow conveyance capacity analyses. Water surface elevation analysis shows that the first scenario caused a drop in surface water elevation by a range of (0.07-0.34) m and a total average of 0.15 m. The second scenario caused a drop in surface water elevation by a range of (0.58-1.28) m and a total average of 0.89 m. The third scenario caused a drop in surface water elevation by a range of (0.26-0.59) m and a total average of 0.43 m as shown in Table 2.

The stream velocity analysis shows that the first scenario leads to an average increase in stream velocity by a percentage of 3.8%. The second scenario reduced velocity by 1.2%. The third scenario leads to a reduction in velocity by 8.4%.

The maximum conveyance capacity analysis shows that the first scenario increased the branch maximum conveyance capacity by a percentage of 33% making it reach 40 million m^3/day before any land inundation occurs on the left or right banks. The second scenario increased the branch maximum conveyance capacity by a percentage of 66% making it reach 50 million m^3/day. The third scenario increased the branch maximum conveyance capacity by a percentage of 33% making it reach 40 million m^3/day.

The inundated land analysis shows that the first scenario caused a reduction in inundated lands by a range of (7.6-52.2) % with a total average percentage of 21%. The second scenario caused a reduction in inundated lands by a range of (16.3-72.9) % with a total average percentage of 34.3%. The third scenario caused a reduction in inundated lands by a range of (13.9-70.8) % with a total average percentage of 32.5% as shown in Figure 7 and Table 3.

Conclusion

The conclusion of this study can be summarized as follows:

- The generated numerical model was successfully implemented by its capability of representing the study area's geometric and morphodynamic characteristics to accomplish this study objective.
- Morphological changes evaluation from the numerical model application shows that the prevailing trend is deposition in the Rosetta branch.
- Results show that during a period of 17 years from 2003 to 2020 the amount of deposition and erosion was found to be 12.6 and 5.8 million m^3 respectively, and annual maximum deposition and erosion rate are 22 and 12 cm respectively.
- Rosetta branch experienced a reduction in the maximum conveyance capacity by a percentage of 25%. The maximum flow discharge the branch can convey is 30 million m^3/day in comparison with 40 million m^3/day during the year 2003.
- The second proposed scenario is considered the optimum solution of the three scenarios as it increased the maximum conveyance capacity of the Rosetta branch to 50 million m^3/day, reducing inundated land area by an average percentage of 21%, and reduced average stream velocity by 3.8%.
- Dredging operations cause a direct and immediate impact on increasing maximum conveyance capacity but have disadvantages on lowering surface water elevation and operations cost.

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Data availability statement

All data, models, or code generated or used during the study are available from the corresponding author by request.

Tables

Table 1. Water level and velocity calibration and verification data sets

Water level calibration data set (Boundary condition)

Year	Discharge in (million m^3/day)	Discharge in (million m^3/day)	Water level in (m)
2021	5	5	2.9
Velocity Calibration Data Set	Velocity Calibration Data Set	Velocity Calibration Data Set	Velocity Calibration
C.S 1 at Km 37.5	C.S 1 at Km 37.5	C.S 2 at Km 37.6	C.S 2 at Km 37.6
Water level verification data set	Water level verification data set	Water level verification data set	Water level verificat
Year	Discharge in (million m^3/day)	Discharge in (million m^3/day)	Water level in (m)
2018	12.5	12.5	2.9
Velocity verification data set	Velocity verification data set	Velocity verification data set	Velocity verification
C.S 1 at Km 146.4	C.S 1 at Km 146.4	C.S 2 at Km 146.5	C.S 2 at Km 146.5

Table 2. Average decrease in surface water elevation after each scenario in relation to different flow discharges

The average drop in water elevation after each scenario (m)	**Flow discharge (million m^3/day)**	**Flow disch**
	5	12.5
First scenario	0.34	0.25
Second scenario	1.28	1.08

Third scenario	0.59	0.40

Table 3. The area of the inundated land in its current state and after each rehabilitation scenario, and flooded land reduction percentage in relation with various flow discharges

Inundated Land (km^2)	Flow discharge (million m^3/day) 30	Flow discharge (million m^3/day) 40	Flow discharg 50
Year 2020	**0**	3.5	6.3
After first scenario	0	**0**	3
Flooded land reduction percentage %	—	—	52.2
After second scenario	0	0	**0**
Flooded land reduction percentage %	—	—	—
After third scenario	0	**0**	0.5
Flooded land reduction percentage %	—	—	—

Figures legend

1. Figure 1: Methodology flow chart.
2. Figure 2: Study area layout and characteristics.
3. Figure 3: Mesh generation; (a) mesh layout; (b) mesh bathymetry; (c) mesh boundary conditions.
4. Figure 4: Calibration process: (a) study area; (b) velocity calibration cross-sections; (c) model, field observed velocity and model performance; (d) velocity cross section at km 37.5; (e) velocity cross section at km 37.6; (f) longitudinal profile of surface water elevation for flow discharge Q=5 million m3/day.
5. Figure 5: a) longitudinal profile of change in bed elevation in relation to minimum flow discharge Q=5 (million m3/day) after each rehabilitation scenario; b) layout of specified contraction locations, underforming islands, and shallow depth areas for the third scenario.
6. Figure 6: Hydrological analysis: (a) rating curve of Rosetta barrage before and after AHD construction; and longitudinal profile of surface water elevation for years 2020 and 2003 at flow; (b) Q=5 million m3/day; (c) inundated land area in each flow discharge during the year 2003 and 2020; (d) and longitudinal profile of surface water elevation for Q=12.5 million m3/day; (e) average increase in water elevation between the year 2020 and 2003; (f) and longitudinal profile of surface water elevation Q=90 million m3/day.
7. Figure 7: Rehabilitation scenarios impact on conveyance capacity and inundated land; (a) inundated land area in current state and after each scenario; (b)inundated land reduction after each scenario in relation with different flow discharges; (c) average inundated land area reduction after each scenario; (d) table of inundated land area in current state and after each implemented scenario.

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