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Identifying manning roughness coefficient using automatic calibration method and simulation of pollution incidents in the Nile River, Egypt

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ABSTRACT

Study region: A reach of the Nile River located between Naga Hammadi barrage and Asyut barrage, Egypt
Study focus: An accurate representation of hydrodynamics of an important water source helps cope with expected future climate changes, pollution incidents and water quality problems. Here, a comparison between HEC-RAS 1D and TELEMAC-2D model was conducted by identifying different Manning coefficients. Moreover, an automatic calibration using Dual-Annealing optimization method was applied for first time to calibrate the model with non-uniform Manning coefficients. The transport of tracer (pollution) was simulated by computing tracer residence times. Pollution transport scenarios were discussed to draw a picture of pollution incidents which will continue to happen in the future. An equation indicating the relation between flow discharge and residence time was derived to hurriedly help decision makers in water management during sudden pollution incidents.
New hydrological insights for the region: A model with spatially variable Manning coefficients using TELEMAC-2D was set up and calibrated achieving good accuracyies with average errors of approximately 4 cm and 7 cm between field and simulated water levels for two different discharge scenarios. Moreover, an equation for relation between flow discharge and residence time was derived producing a strong correlation coefficient of 0.95. This study, integrating advanced hydrodynamic models and automatic calibration techniques, provides a robust framework for assessing and managing water resource challenges under varying flow conditions.

1. Introduction

Egypt's culture, history and its present and future environmental sustainability are irretrievably related to the Nile River. For the hyper-arid country of Egypt, the Nile River is regarded as the main and almost only water source for drinking, agriculture, fishing and other life-sustaining activities with a percentage of 93 % of its water requirements. A fixed average annual share of 55.5 billion m^3 of water in the service of over 105 million people should be quantitively and qualitatively well-preserved to maintain the development of

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the country. Moreover, the Nile River in Egypt is surrounded by different present and expected future circumstances, which should be flawlessly handled. For instance, Egypt is vulnerable to severe scarcity and drought problems associated with the present conditions of a rapidly increasing population. Also, the expected climate change will increase the deviation range of the flow of the Nile by approximately 50 %, which means more occurrence of flood and drought conditions. Different expected drought and flood conditions will have effects on water levels, flow velocities, navigation, hydropower stations and water quality of the river. In this regard and in coping with the heightened danger to the water supply in Egypt, proper and highly accurate hydrodynamic investigations have been regarded as a national obligation for safeguarding the long-term development of the country.

Both the field investigations and numerical simulation of the Nile's hydrodynamics are essential for maintaining the water quantity for the lifeblood of Egypt, each with its importance. For instance, field investigations provide an accurate representation of the flow hydrodynamics and help to calibrate the numerical results, however, field studies consume time, effort and cost. The National Water Research Center (NWRC) provides an understanding of the hydrodynamics at various areas along the main Nile, as well as in irrigation canals and main drains, at various low-flow discharges during the winter and high-flow discharges during the summer. Besides field investigations, numerical simulations can aid in providing a comprehensive understanding of the management of water hydrodynamics and spatial and temporal identification of physical, chemical, and biological aspects of water. In this regard, numerical simulations calibrated with the proper field investigations can assist professionals, agencies, resource managers, planners and decision-makers in understanding different river flow scenarios and future risks.

In the last decades, many researchers began to shed light on the investigation of the Nile River's hydrodynamics and sediment transport by applying different 1D, 2D and 3D models. For instance, (Elsayed et al., 2019; Omar et al., 2022; Mostafa, 2012; Samir et al., 2019) applied the HEC-RAS 1D model, as the most famous 1D model, for investigation of hydrodynamics and sediment transport in different reaches of the Nile River. While different morphological changes of different reaches of the Nile River were investigated using different 2D models e.g., (Said et al., 2014) applied the GSTARS 2.0 model, (Mahgoub et al., 2015) used TELEMAC-2D, (Sattar and Raslan, 2014; Negm et al., 2017) applied the CCHE-2D model and (Gaweesh et al., 2020) applied Delft3D. Deciding 1D, 2D or 3D models and the degree of obtained accuracy varies depending on the level of the regularity of cross-sections, the degree of bend and the presence of hydraulic structures (Moussa, 2020). Moreover, choosing 1D, 2D, or 3D models depends on the topic of interest and the datasets at hand, especially the applied measurements to calibrate the model. 1D models are advantaged by acceptable results of hydrodynamics for regular cross-sections in straight channels in low computation time. On the other hand, problems of simple 1D models increase with the increase of the level of complexity of the river as less accurate results are expected in irregular cross-sections and bent channels. In this regard, 2D models are gaining prominence in the hydraulic engineering industry seeking more accurate results for complex domains and thanks to advancements in computer technology and 2D modeling engines. Also, 2D models provide a real continued topographic flow environment represented by a series of mesh elements and can represent both the lateral and longitudinal directions. Moreover, 2D models like Mike 21, Mike 21 FM, or TELEMAC-2D can also be useful tools to investigate the water quality, control pollution transport and simulate the residence time of biochemical pollutants or oil spills with highly accurate results (Zavattero et al., 2018; Li and Yao, 2015). Also, 3D models show importance in complex phenomena such as the simulation of water salt intrusion in estuaries of rivers. For instance, (Mahgoub, 2015) set up a 3D model for the Nile Estuary to simulate the hydrodynamics and salinity transport from the Mediterranean Sea in the Nile's water.

An accurate hydrodynamic representation (water depth and flow velocity) of any water system is the first and the main step toward a high-quality model that has a great ability to discuss different complex problems in multiple hydrologic and hydraulic applications such as expected future climate change scenarios with droughts and floods, sediment transport and water quality simulations (Abouelsaad et al., 2023, 2022a). Precise model calibration is the principal task that will ensure the quality of the proposed model. Channel roughness plays a significant role in calibrating the hydrodynamics of a natural river, which represents the frictional resistance to the gravity of water flow (Ardıçlıoğlu and Kuriqi, 2019). Manning law is one of the common laws, that represents channel roughness, flow residence and energy loss. Several authors researched the attitude of the Manning coefficient and the affecting parameters such as (Nimnim and Farhan, 2015; Prajapati et al., 2016; Teixeira et al., 2018; Zink and Jennings, 2014). It was found that Manning coefficient is a tricky, highly variable and sensitive parameter having a value depending on particle size, channel irregularities, surface roughness, meandering, changes in water depth, channel bottom slope and other river characteristics (Ong et al., 2017). In this regard, the adoption of a proper Manning coefficient is a challenging process despite its high effect on flow hydrodynamics. Although, different recent and previous research have studied the Manning coefficient, uncertainties remain in estimating the appropriate roughness coefficient. Manning coefficient can be manually or automatically calibrated. Manual calibration is an extremely time-consuming process, in which different trial and error processes are applied until deviations between model results and field measurements are minimized to a satisfactory limit. For instance, (Islam et al., 2018; Kumar, 2018; Panda et al., 2010) have manually calibrated the parameter considering the significant sensitivity of the Manning coefficient on model hydrodynamics. It becomes a more frustrating process with lower accuracy affected by the complexity of the model in increasing number of dividing sections, number of parameters and field data of water depths and different discharges. Consequently, automatic calibration with the aid of High Performance Computing (HPC) systems and machine learning are gaining consideration in order to minimize the difference between observed data and simulation results in an effective way with the least errors in low times (Kan et al., 2019). The proper simulation of flow hydrodynamics is considered the basis for more complex processes such as water quality simulations, residence time and transport processes.

The transport process of tracer or pollution in water bodies is a highly important process to maintain the water's health. Understanding the residence time of pollution and how long polluted water is completely flushed from the domain is vital to control the current water pollution (de Pablo et al., 2022). The most classic definition of water residence time is the time consumed by any water particle (or polluted water) to leave the domain from its outlet. The residence time of water (or pollution) is an important indicator of contaminant persistence and biogeochemical cycling. Simply, the residence time can be computed as the time required for the tracer quantity to be flushed out of the domain until the retained quantity reached, for example, 10 % of the total initial amount (Abouelsaad et al., 2022b; Matta, 2018). Understanding the fate and transport of water pollution in water bodies and how quickly water is flushed for water bodies is critical, especially in times of pollution accidents.

In the last decade, many incidents of sudden pollution have been reported in different locations of the Nile River. For instance, in 2012, an oily spot leaked into the Nile River near Aswan city (beside Aswan Dam, southern Egypt, as shown in Fig. 1). The diameter of the patch reached 5 km, which led to the suspension of drinking water stations in Aswan. Also, in the same year, a factory in Naga Hammadi city (beside Naga Hammadi barrage, as indicated in Fig. 1) discharged its petroleum residues into the Nile River causing the formation of an oil slick about 50 m wide and 1 km long. Also, in 2014, a tourist boat in Aswan city caused an oil slick to spill into the Nile in Aswan, which moved with the discharged water of the Nile. Moreover, in 2015, a river tanker carrying 510 tons of phosphate sank in the Nile River in Qena Governorate, south of Egypt (Fig. 1). Some of those incidents led to the cutting off of drinking water from some areas due to the suspension of drinking water stations. To date, the effect of concentrated polluted water on water characteristics in the Nile River has not been comprehensively investigated yet, despite the danger that may be caused by those accidents. There are only a few official reports on those pollution incidents.

This work discusses a reach of the Nile River located between the Naga Hammadi barrage and Asyut barrage, known as the 3rd reach of the Nile River. HEC-RAS 1D and TELEMAC-2D models were applied using different Manning coefficients. A precise evaluation of the Manning coefficient gives an accurate insight into the flow velocities and flow hydrodynamics, which is considered a fundamental step toward studies of the reach's pollution problems and water quality investigations. 1D simulations are built depending on more modelling simplifications than 2D models such as neglecting transverse velocity and transverse variations in the water surface. Consequently, the optimum Manning values in model calibration using both models may differ and consequently the accuracy in calculating flow velocities and other water characteristics, especially in such complex domains. Firstly, the absolute error of applying the same uniform Manning coefficient in the whole domain was computed using both models. Afterward, as non-uniform Manning coefficients are expected for a 180 km reach of study, different Manning coefficients were checked seeking less error and a good hydrodynamic using 2 different flow discharges. In this regard, automatic calibration was applied to calculate the values of the Manning coefficient leading to the minimum error between the field and simulated results using the Dual-Annealing optimization method, which was applied for the first time for hydrodynamics calibration process of water systems such as rivers. With the improvements of computational power provided by HPC systems, a large number of optimization techniques have been proposed in the last years to solve different complex calibration processes such as (Tügel et al., 2021; Hassan et al., 2022; Theodossiou et al., 2014; Vrugt et al., 2003; Zhu et al., 2021). The calibration procedure should always be based on the model and user requirements (Osaba

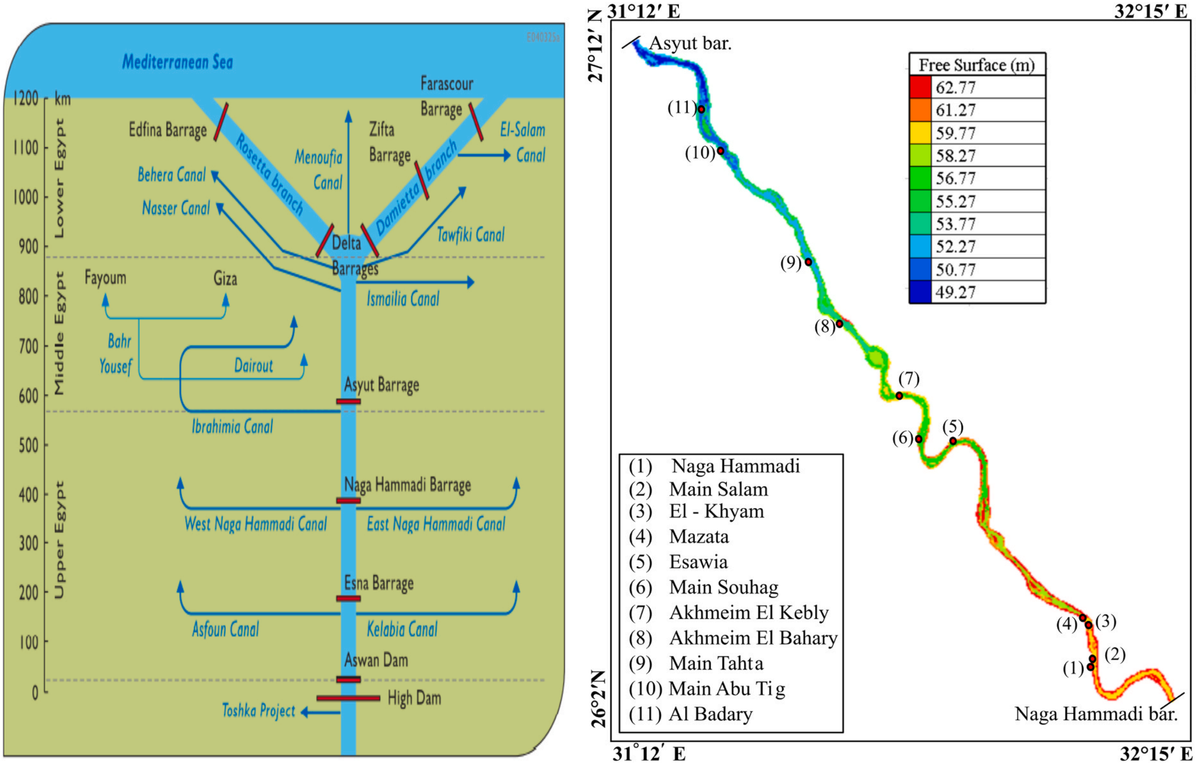

Fig. 1. Schematic for the main control structures on the Nile in Egypt (MWRI, 2005) (left) and zooming to the studied area in upper Egypt showing the drains in the reach (right).

et al., 2021; Piccolroaz et al., 2024). In this work, the Dual-Annealing optimization method was applied within the Automated Calibration Tool for Shallow Water Models (ActSwm) tool, a method previously proven effective by (Hassan et al., 2022) in the automatic calibration of shallow water flow models. In this work, this method was selected after comparing its performance with other global optimization methods available within ActSwm, due to its success in terms of accuracy and computational cost.

After the detailed insight into the hydrodynamics of the Nile River, especially with the 2D model, the tracer transport was simulated to investigate the transport process and the pollutant's residence time. This study can be considered as the first simulation of the Nile's repeated accidents. Pollution residence time is expected to be highly affected by the applied flow discharge. In this regard, the relation between the residence time and different flow ranges in summer and winter was conducted. For all previously mentioned pollution accidents and the expected upcoming incidents, calculations of the residence time of polluted water and its relation to the applied discharge are essential to overcome such incidents and to help decision-makers control their negative effects.

The main aims of this work can be summarized as follows:

1. Comparison between the calibrated Manning coefficient using 1D and 2D models while applied in a long reach of the lifeblood of Egypt, the Nile River
2. Application, for the first time, of an automatic calibration technique of spatial non-uniform Manning coefficient using TELEMAC-2D considering different flow discharges
3. Simulation of the effects of sudden pollution incidents in the river and their residence time considering different flow discharges

In conclusion, this study presents a comprehensive and precise examination of one of the world's most crucial water resources, the Nile River, through advanced hydrodynamic analysis and pollution incident modeling. By effectively comparing 1D and 2D river modeling techniques, this research not only contributes significantly to our understanding of the Nile's complex flow dynamics and pollutant transport but also establishes a robust framework for river management strategies. This research serves as an instrumental tool in navigating the challenges of river management, especially in the face of evolving environmental pressures and future impacts. Thus, it marks a pivotal step towards sustainable water resource management on a global scale, reinforcing the critical role of scientific innovation in addressing contemporary and future environmental challenges.

2. Study area and data

The Nile River flows through Egypt from Aswan to the Mediterranean Sea with a length of approximately 1200 km. In upper Egypt, the Nile River is divided into four main reaches specified with five barrages (as shown in Fig. 1) that help control the flow and divert water into the main irrigation canals without lifting stations. The 3rd reach investigated herein is located between the new Naga Hammadi barrage and Asyut barrage with a length of approximately 180 km. The study region catches polluted water from 11 drains, as depicted in Fig. 1, and supplies water for El-Ibrahemia major canal upstream of Asyut barrage.

The geometry of the studied reach was considered using data from the most recent hydrographic survey investigated by the Nile Research Institute (NRI) at the National Water Research Center in May 2019. Bottom elevations of 721 cross sections of the Nile River in the 180 km reach were applied for precise model generation in both HEC-RAS 1D model and TELEMAC-2D model. The average width of the 3rd reach is approximately 1400 m (ranging from 700 m to 3500 m). Moreover, data about the inflow discharge at Naga Hammadi barrage and outflow water level upstream Asyut barrage were collected for the period from 2000 to 2018. For the whole period, the monthly average discharge from the Naga Hammadi barrage ranged from 775 m^3/s in winter to 2454 m^3/s in summer. Also, the minimum and the maximum monthly registered flow discharges were found to equal 46 million m^3/d and 228 million m^3/d, respectively. Data about flow discharges of minimum, average and maximum monthly flows for the period from 2000 to 2018 are shown in Fig. 2. On the other hand, the outflow water level at Asyut barrage ranged from 46.6 m to 50.7 m. At six control points along

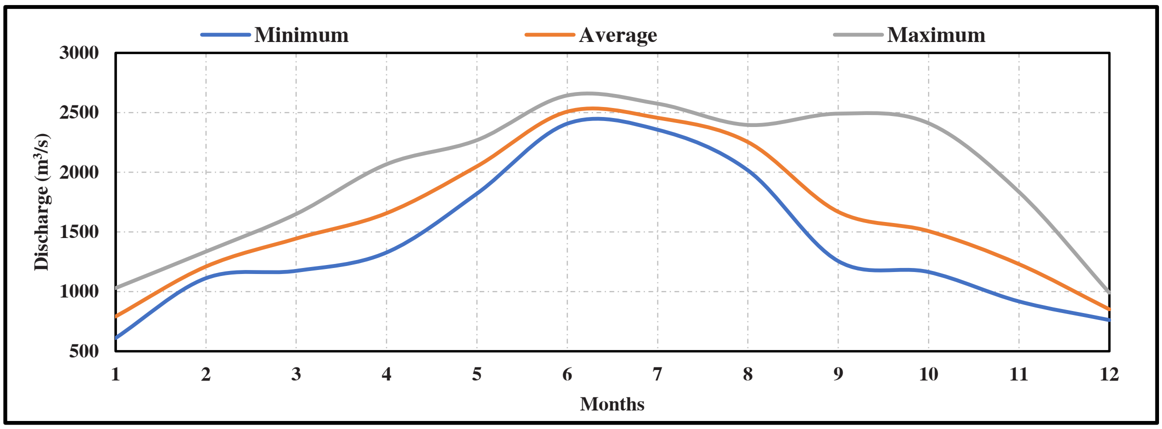

Fig. 2. Minimum, average and maximum flow discharges for each month during the period from year 2000 to 2018 at the 3rd reach of the Nile Rive.

the reach (shown in Fig. 3), the water surface elevation and the corresponding flow discharges are determined daily. Moreover, the studied area receives polluted drainage water from 11 drains, with discharge percentage of the total Nile discharge ranging approximately from 0.3 % to 1.65 % of Nile inflow discharge during the winter or summer seasons.

3. Materials and methods

3.1. HEC-RAS 1D model

HEC-RAS 1D modelling system is one of the most widespread programs used for hydraulic analysis. It performs one-dimensional calculations for networks of natural or manmade channels by solving the 1D Saint-Venant equations of continuity and momentum (Brunner and Bonner, 2010). Saint-Venant equations in 1D flow are solved using a finite difference scheme for sub- or super-critical flow conditions, steady and unsteady flows (Hamdi and Brunner, 2002). In the HEC-RAS model, the most successful procedure is applying the four-point implicit scheme as described in (Brunner and Bonner, 2010).

As a one-dimensional model, flow is treated in the longitudinal direction (Hamdi et al., 2019). It neglects the transverse velocity, momentum and variations in the water surface. The continuity equation and the momentum equation describing the flow in 1D models are indicated in Eqs. 1 and 2 as follows:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial\left(\frac{Q^2}{A}\right)}{\partial x}+gA\frac{\partial H}{\partial x}+gA\left(S_0-S_f\right)=0 \tag{2}$$

Where A is the cross-sectional area normal to the flow (m^2), Q is the discharge (m^3/s), g is the gravity acceleration (m/s^2), H is the elevation of the water surface above a specified datum (m), S_0 is the bed slope, S_f is the energy slope, t is the time (s) and x is longitudinal coordinate (m).

HEC-RAS 1D model offers two different coefficients to calculate the bottom friction: Manning coefficient (n) and equivalent roughness (k). HEC-RAS provides reference values for the Manning coefficient for different common types of channels as indicated in (Chow, 1959). While equivalent roughness (k) is a measure of the linear dimension of roughness elements and depends on changes in shape and orientation of the channel.

Geometry data in simulations using HEC-RAS 1D model is exported using ArcGis program. On the other hand, HEC-RAS does not

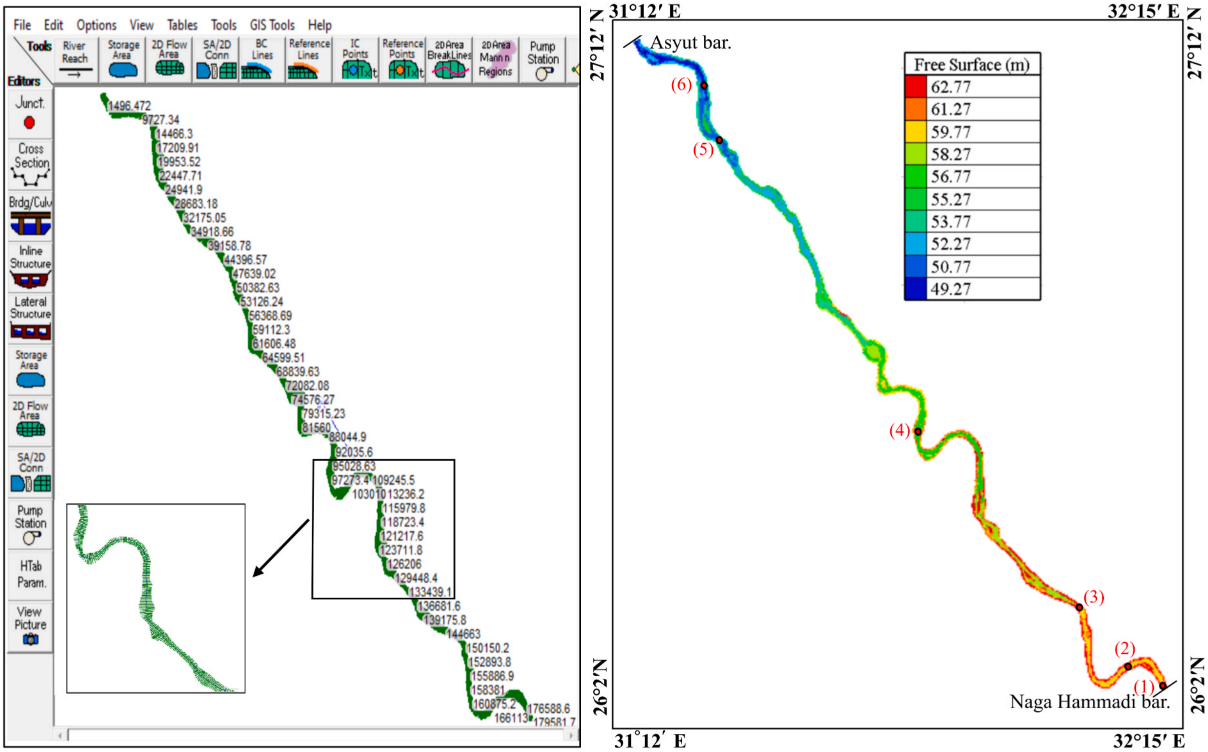

Fig. 3. Screenshots of the applied models of HEC-RAS 1D model (left) and TELEMAC-2D model and the 6 observation points along the reach (right).

depend on any different pre- or post-processing tools. In this regard, the application of different boundary condition scenarios and visualization of output results are produced using the HEC-RAS model.

3.2. TELEMAC-2D model

TELEMAC-2D solves the two-dimensional non-conservative form of Saint-Venant and transport equations with complex algorithms mostly based on the Finite Element Method. The idea behind the finite element method is the domain subdividing into many small finite elements using triangle or quadrilateral shapes. TELEMAC-2D computes the water depth, both flow velocities in x and y directions and the tracer concentration at each point of the generated mesh (Hervouet and Ata, 2017). In this regard, one or more of eight different numerical schemes can be applied to solve the advection and propagation diffusion equations such as different explicit or implicit techniques, the PSI distributive scheme and the method of characteristics scheme. Using FORTRAN scripts, different natural phenomena can be simulated such as the effects of bottom friction, rain, tracer transport (mass conservative), wind, evaporation as well as the particle tracking (Hervouet and Ata, 2017).

The water flow governing equations are the continuity equation, the momentum equations in x- and y- directions and the tracer equation as follows:

$$\frac{\partial \mathrm{h}}{\partial \mathrm{t}} + \vec{\mathrm{u}} * \mathrm{grad}\ \mathrm{h} + \mathrm{h}\mathrm{div}\vec{\mathrm{u}} = S_h \quad (3)$$

$$\frac{\partial u}{\partial \mathrm{t}} + \vec{u} * \mathrm{grad}\ \mathrm{u} = -\mathrm{g}\frac{\partial Z}{\partial \mathrm{x}} + S_x + \frac{1}{\mathrm{h}}\mathrm{div}(h\nu_t \mathrm{grad}\ \mathrm{u}) \quad (4)$$

$$\frac{\partial v}{\partial \mathrm{t}} + \vec{u} * \mathrm{grad}\ \mathrm{v} = -\mathrm{g}\frac{\partial Z}{\partial \mathrm{y}} + S_y + \frac{1}{\mathrm{h}}\mathrm{div}(h\nu_t \mathrm{grad}\ \mathrm{v}) \quad (5)$$

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} + \vec{u} * \mathrm{grad}\ \mathrm{T} = \mathrm{S}_T + \frac{1}{\mathrm{h}}\mathrm{div}(h\nu_T \mathrm{grad}\ \mathrm{T}) \quad (6)$$

Where h is the water depth (m), u, v are velocities along x-direction and y-direction (m/s), x, y are horizontal space coordinates (m), T is the tracer (g/l), S_h , S_T are the sources or sinks of fluid (m/s) and tracer (g/l/s), v_t is the turbulent viscosity, v_T is the turbulent diffusivity (m^2/s), Z is the free surface elevation (m), t is time (s) and S_x ,S_y are source or sink terms in momentum equations (m/s^2).

Bed friction is considered one of the most important sink parameters in momentum (Abouelsaad et al., 2022b; Abouelsaad, 2023). TELEMAC-2D offers the application of several formulas to calculate the bottom friction such as Strickler's law, Manning's law, Chézy's law and other friction laws may be used (Hervouet, 2007). In this work, the bottom friction followed Manning's law:

$$f_x = \frac{u}{\cos(\alpha)}\frac{gn^2}{h^{4/3}}\sqrt{u^2+v^2} \quad (7)$$

$$f_y = \frac{v}{\cos(\alpha)}\frac{gn^2}{h^{4/3}}\sqrt{u^2+v^2} \quad (8)$$

Where α is the angle of bottom slope and n is Manning coefficient.

TELEMAC model has no graphical interface, consequently, it requires the use of pre- and post-processing tools. Blue Kenue was applied as a pre-processing tool for mesh generation and creating boundary condition file, which defines different specified boundary condition values for water depth, flow velocity, discharge or tracer. It can produce geometry files in SERAFIN/SELAFIN (.slf) format and boundary condition file as CONLIM table (.cli), which are required by TELEMAC. Moreover, Blue Kenue and Paraview were applied as a post-processing tools to extract information from the result files to visualize and analyze them. Blue Kenue has the capability to visualize the SELAFIN result file generated by TELEMAC without the time-consuming process of the crucial converting of the SERAFIN result file to any different formats such as the Visualization Toolkit (VTK) format required by ParaView.

3.3. Automatic calibration Dual-Annealing using optimization

Many models of shallow water equations depend on manual calibration of parameters and this process may consume much effort and time in 2D models. Also, manual calibration of 2D models may fail to get accurate results, especially when complicated domains are investigated, high number of validation results are available or equations have too many parameters like in water quality simulations. In this regard, automatic calibration using HPC systems can easily calibrate a large number of parameters in a relatively short time and with high accuracy. To carry out an automatic calibration of the Manning coefficient in the 3rd reach of the Nile River, ActSwm is used. It is an open-source, Python-based tool developed at the Chair of Water Resources Management and Modeling of Hydrosystems of the Technische Universität Berlin, Germany. In this regard, the Dual-Annealing optimization method was applied for calibration of free surface at 6 observation points using 2 different flow discharges and the corresponding free surfaces along the 3rd reach of the Nile River. The Dual-Annealing optimization method is a stochastic approach, which combines the generalization of both the classical simulated annealing and fast simulated annealing (Xiang and Gong, 2000; Hassan et al., 2021; Hassan et al., 2022). Firstly, the optimization engine chooses a value for each parameter constrained by two boundary values (suggested by the user) to be solved by

TELEMAC-2D model. Different objective functions can be computed to calculate the accuracy of the obtained results. Herein, the TELEMAC-2D results are returned to the optimization method using Python script to calculate the objective function of absolute variation between the simulated and field results. The optimization engine then chooses whether to halt the simulation after obtaining a certain accuracy or to restart the operations using new parameter values based on the convergence criterion.

4. Model setup and simulation scenarios

4.1. Model setup

Both HEC-RAS 1D and TELEMAC-2D models were applied to simulate the 3rd reach of the Nile River. Fig. 3 shows screenshots of HEC-RAS 1D model and TELEMAC-2D model and the 6 observation points. The bed topography was investigated using approximately 721 sections spaced 250 along the reach. The area is subjected to a seasonal inflow at new Naga Hammadi barrage and the corresponding outflow from Assuit barrage. Moreover, 11 drains throw their effluent at different locations in the Nile and one outflow goes to El-Ibrahimya canal. In both models, an inflow boundary condition at Naga Hammadi barrage with discharge equals 2560 m^3/s in summer and 645 m^3/s in winter and an outflow boundary condition of 50.3 m and 48.25 m in summer and winter, respectively were applied. Moreover, data about the inflow from 8 lateral drains (neglecting small secondary drains) were considered from an Egyptian report conducted in 2013 (Wahaab, 2013).

For the HEC-RAS 1D model, google satellite images were imported to the ArcGIS tool to trace the alignment of the reach. The cross-sectional data were generated using Hec-GeoRAS tool on ArcGIS and imported to the HEC-RAS. 721 nodes spaced 250 m were investigated depending on the available field data. In HEC-RAS model, the flow governing equations are solved using the most accepted procedure in 1D flow of the four-point implicit scheme, known as the box scheme. Different Manning coefficients were manually applied for model calibration (using different manual trial and error scenarios) seeking highly accurate water surface values compared with field water surfaces under the effect of the minimum and the maximum flow discharges. An initial flow discharge of the upstream flow discharge was applied and increased by the inflow discharge from the vicinity drains along the studied reach.

For the 2D model, Blue Kenue software was used for mesh generation and creation of boundary conditions file. The generated mesh is composed of a total of about 850,000 nodes and 1,350,000 triangular elements with an approximate distance between elements of 18 m. Results of the applied mesh were compared with more refined mesh having approximately spacing of 10 m and they both gave approximate results ensuring grid convergence. In this regard, a mesh of 18 m space between elements was chosen to preserve less computational time.

TELEMAC-2D was applied on the generated mesh to simulate the hydrodynamics and transport of the tracer. In this regard, the method of characteristics was applied using linear discretization for the flow velocities, the PSI method was used for calculations of water depth and edge-by-edge implementation of upwind explicit finite volume (mass-conservative method) was applied in the tracer transport process. A constant viscosity model was adopted for turbulence, in which both the turbulent viscosity and the turbulent diffusivity were set equal to 10^{-6} m^2/s.

For the initial conditions using TELEMAC-2D model, a constant initial water elevation of 63 m above the mean sea level was used over the entire domain while the initial velocities were set to zero. The simulation continued until the steady state was reached to calculate the steady hydrodynamics of water levels and flow velocities. Moreover, 200 parallel processors of an HPC cluster were applied in which a one-day simulation for the 180 km reach of the Nile River took approximately 3 minutes of calculations. Finally, the Blue Kenue and Paraview post-processing tools were utilized to visualize TELEMAC-2D output results.

4.2. Simulation scenarios

Manning coefficient was adopted for the calculation of bottom friction. The literature research for the studied area showed that the Manning coefficient ranges from 0.015 to 0.033 $s/m^{1/3}$ (Heba and Esam, 2013; Sattar and Raslan, 2014; Samir et al., 2019). Consequently, different Manning coefficients, within the literature range, were applied for better calibration by comparing the simulated results with field results. Firstly, the sensitivity of the reach to the same Manning coefficient was investigated. Two different flow discharges were simulated in the calculation of the best Manning coefficients: the maximum flow discharge in summer 2018 (2560 m^3/s and downstream water elevation of 50.3 m) and the minimum flow discharge in winter 2018 (685 m^3/s with water elevation of 48.25 m at the downstream). Moreover, lateral discharges from eight inflow drains and Ibrahimya outflow irrigation canal were also investigated. Field data of water depths for six observed points along the reach were compared with the simulation results.

On the other hand, it is known that the roughness of any river varies among cross sections and its longitudinal direction depending on some factors such as the gameography of the bed, channel's local irregularities, flow discharges and vegetation cover. Consequently, differences in Manning coefficients were assumed over a longitudinal studied distance of 180 km of Nile. In this regard, automatic calibration for Manning coefficients was applied seeking more reliable results with less error using the TELEMAC-2D model.

After the model calibration, the effects of different flow discharges on the water elevations and flow velocities were discussed. Those scenarios are discussed as lower flow discharges are expected in the future affected by the expected climate change.

Afterward, transport processes in the domain were investigated using the calibrated TELEMAC-2D model. The residence time was computed for 36 different flow discharges: the monthly minimum, average and maximum flow discharges for the years 2000–2018, as shown in Fig. 2. Firstly, the steady state was processed for the 36 studied cases. Afterward, a tracer of polluted water from occasional or accidental conditions was injected for only 1 day in the reach with the same tracer concentration of 100 mg/l. The residence time is calculated as the time required for the tracer quantity to be flushed out of the domain until the retained quantity reaches 10 % of the total initial amount. The relation between the flow discharge of the 36 studied cases and the residence time was then computed. Afterward, the domain was divided into small sections to compute the spatial residence time of each 9 section with a 20 km length. Firstly, the same flow discharge of 609 m^3/sec was applied at each reach until the steady state was reached. Afterward, a tracer of 100 mg/l was injected in the domain for only one hour. The residence time was computed at each of the nine reaches to compare different residence times along the computational domain.

5. Results

5.1. Sensitivity analysis of different Manning coefficients

The hydrodynamic model was run to obtain the free surface elevations using different Manning coefficients at 6 observation points (shown in Fig. 3) using both the minimum and maximum flow discharges. Fig. 4 shows the sensitivity analysis of the Manning coefficient considering both discharges by computing the absolute variation between the field and simulated results for the 6 observation points (along the 180 km reach) using HEC-RAS 1D model, while Fig. 5 shows the corresponding sensitivity analysis of Manning coefficient considering both discharges using TELEMAC-2D model. While Table 1 indicates the absolute variation at all points by applying the minimum and the maximum flow discharges and the best Manning coefficients under each flow discharge using 1D model, Table 2 indicates the minimum absolute variation between the simulated and field water elevations using the same optimum uniform Manning coefficient in both flow discharges using HEC-RAS 1D model. Finally, Table 3 indicates the best-chosen Manning coefficient of 0.026 s/$m^{1/3}$ and the corresponding variation between simulated and field data and the summation variation at all points in both flow discharges using TELEMAC-2D model.

It can be indicated from Fig. 4 and Table 1 that the best Manning coefficients are different while applying the minimum and the maximum flow discharge using the HEC-RAS 1D model. The best manning coefficients were 0.036 s/$m^{1/3}$ and 0.028 s/$m^{1/3}$ in both flow discharges: minimum and maximum discharges, respectively. For instance, a Manning coefficient of 0.036 s/$m^{1/3}$ gave

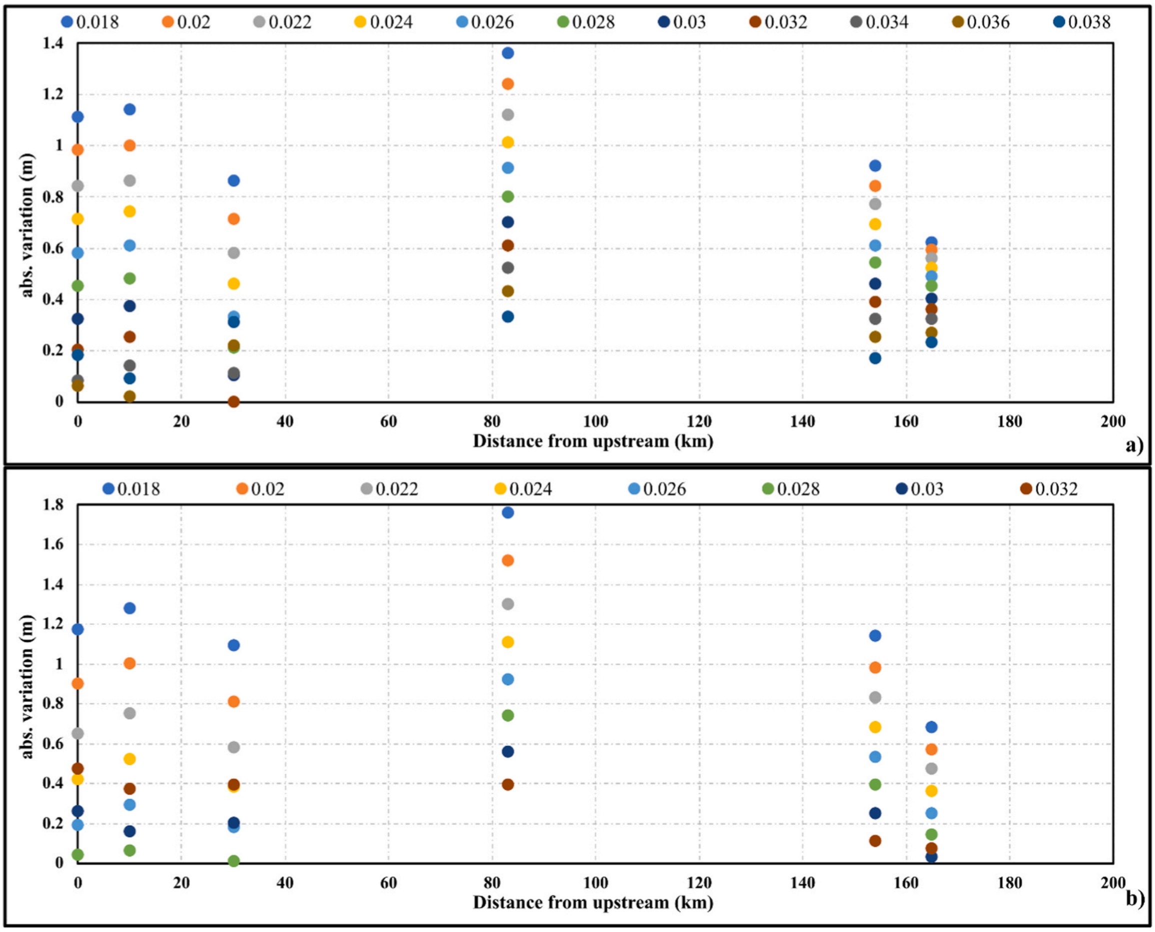

Fig. 4. Sensitivity analysis of Manning coefficients in s/$m^{1/3}$ by computing the absolute variation between the field and simulated results for the 6 observation points (along the 180 km reach) using HEC-RAS 1D model considering a) the minimum discharge and b) the maximum discharge.

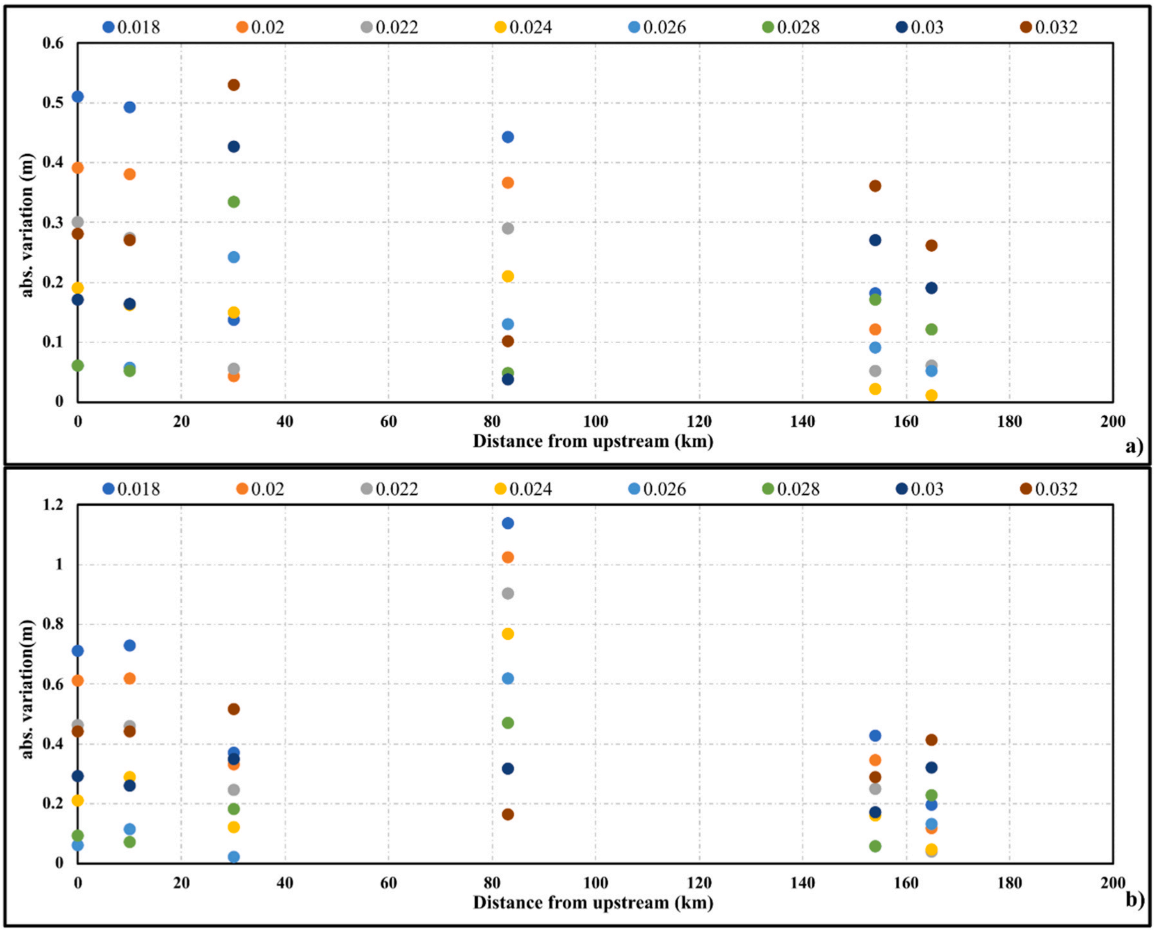

Fig. 5. Sensitivity analysis of Manning coefficients with values range from 0.018 to 0.032 s/m$^{1/3}$ by computing the absolute variation between the field and simulated results for the 6 observation points (along the 180 km reach) using TELEMAC-2D model considering a) the minimum discharge and b) the maximum discharge.

Table 1
Absolute variation (m) between the simulated and field water depths under the effect of the minimum and the maximum flow discharges and different uniform Manning coefficients for different discharges using HEC-RAS 1D model.

	n	0 km	10 km	30 km	83 km	154 km	165	sum
Min. Q	0.036 s/m$^{1/3}$	0.06	0.02	0.22	0.43	0.25	0.27	1.25 m
Max. Q	0.028 s/m$^{1/3}$	0.04	0.06	0.01	0.74	0.39	0.14	1.38 m

Table 2
Absolute variation (m) between the simulated and field water depths under the effect of both the minimum and the maximum flow discharges using the same uniform Manning coefficient using HEC-RAS 1D model.

	n	0 km	10 km	30 km	83 km	154 km	165	sum
Min. Q	0.032 s/m$^{1/3}$	0.47	0.37	0.39	0.39	0.11	0.07	1.80 m
Max. Q	0.032 s/m$^{1/3}$	0.2	0.25	0.00	0.61	0.39	0.38	1.81 m

approximately a sum error of 1.25 m considering the minimum flow discharge of 609 m^3/s. On the other hand, a Manning coefficient of 0.036 s/m$^{1/3}$ gave approximately a sum error of 1.38 m considering the maximum flow discharge of 2645 m^3/s. Those results show that applying the same Manning coefficient for all flow discharges using the 1D model may produce high errors between field and simulated results. Moreover, applying the same Manning coefficients in both flow discharges produces higher errors as shown in Table 2. As shown in Table 2, approximately 1.80 m error was computed in both flow discharges using the same Manning coefficient of 0.032 s/m$^{1/3}$.

Table 3
Absolute variation (m) between the simulated and measured water depths under the effect of both the minimum and the maximum flow discharges with the best uniform Manning coefficient using TELEMAC-2D model.

	n	0 km	10 km	30 km	83 km	154 km	165	sum
Min. Q	0.026 s/m$^{1/3}$	0.06	0.06	0.24	0.13	0.09	0.05	0.63 m
Max. Q	0.026 s/m$^{1/3}$	0.06	0.11	0.02	0.62	0.05	0.13	0.99 m

On the other hand, using the TELEMAC-2D model, it was found from Fig. 5 and Table 3 that the total variation for the 6 observation points equals 0.63 m and 0.99 m under the effect of minimum and maximum flow discharges. In TELEMAC 2D, the best Manning coefficient of 0.026 s/m$^{1/3}$ was obtained by applying both flow discharges. In this regard, TELEMAC-2D is less sensitive to changes in flow discharges and can be applied for different flow discharges giving a reasonable error.

It can be concluded that the best Manning coefficients using HEC-RAS 1D model and TELEMAC-2D MODEL are different and equal 0.032 and 0.026 s/m$^{1/3}$, respectively. Also, it was found that 1D model is more sensitive to changes in Manning coefficients than 2D model and gives larger errors in results.

On the other hand, it can be indicated from both figures (Fig. 4 and Fig. 5) that the optimum Manning coefficient changes with the studied reach between any observation points. In this regard, the TELEMAC-2D model was applied in the following scenarios as it gave more accurate results and was less sensitive to changes in flow discharges. Automatic calibration for Manning coefficient with the help

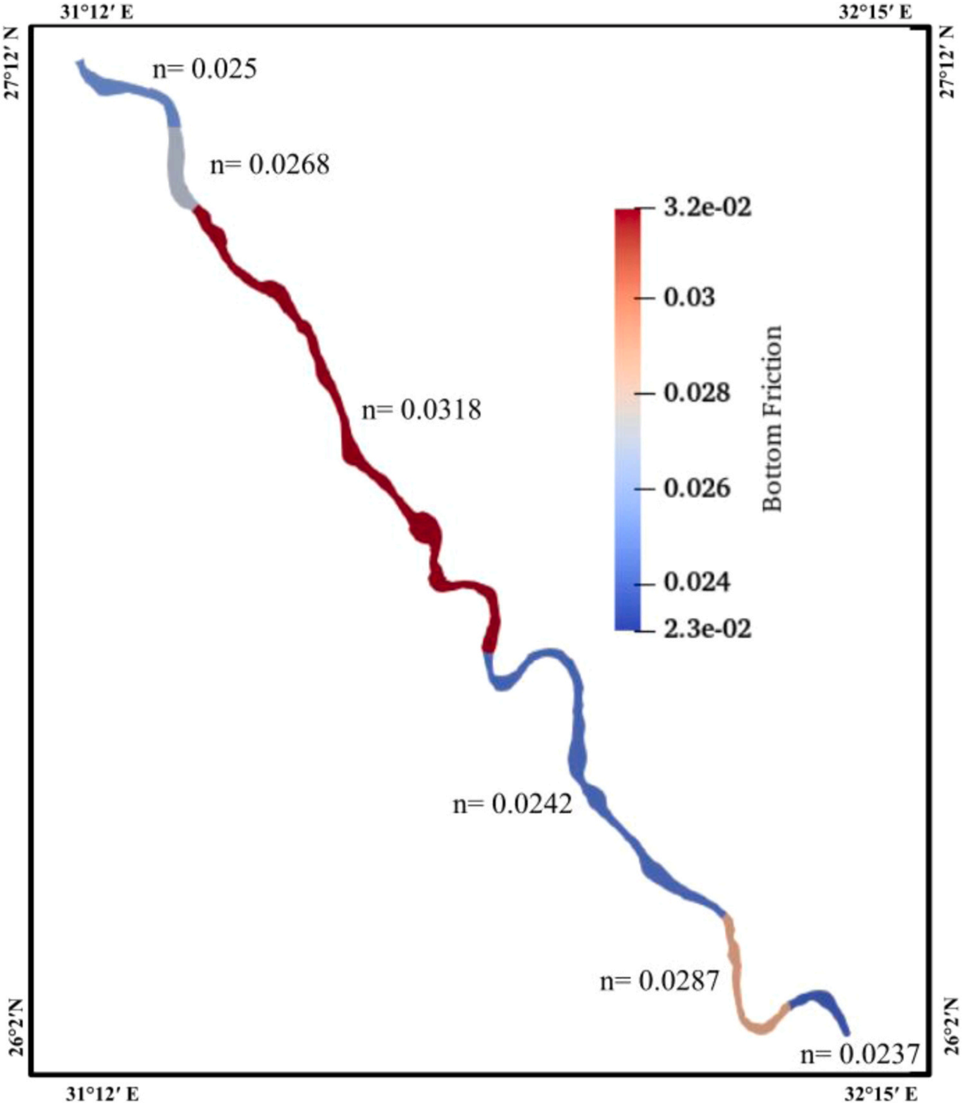

Fig. 6. Screenshot from Paraview for the automatically calibrated Manning coefficients in the 6 sections.

of HPC systems was applied seeking smaller errors and more precise hydrodynamic simulations.

5.2. Automatic calibration of Manning coefficient using TELEMAC-2D model

In the previous case, a constant Manning coefficient for the whole domain gave relatively high errors, especially in the middle part of the domain. The reason behind this was that the middle part of the domain has a different range of Manning values than the assumed one. In this regard and seeking a more reliable representation of the Nile hydrodynamics, the Nile was divided into 6 sections with different Manning coefficients. The model was automatically calibrated using the minimum flow discharge of 685 m^3/s with a water elevation of 48.25 m and the high discharge scenario using 2560 m^3/s and a water elevation of 50.3 m. The domain was divided into 6 sections, each bound by two field observation points. The Dual-Annealing optimization method was applied to optimize the Manning coefficient in each section. The calculation time was approximately 10 minutes per iteration until the steady state was reached in each scenario. The results show the objective function begins to converge after 20 trials using different values of Manning coefficient at each reach. 20 trials mean a total simulation time of approximately 3 hours. Fig. 6 shows the applied Manning coefficients in the 6 sections using automatic calibration, while Fig. 7 shows the simulated and field free surface elevations using both discharges. Moreover, Table 4 shows the variation between simulated and field data and the summation variation at all points using the automatically calibrated Manning coefficients.

While comparing the results of the same Manning coefficient of 0.026 $s/m^{1/3}$ as shown in Table 3 and the results of the automatically calibrated Manning coefficients in Table 4, the automatically calibrated Manning coefficients gave more accurate results. For instance, the total variation (m) between the simulated and field water depths decreased from 0.63 m to 0.25 m in the case of the minimum flow discharge. Also, the mentioned total variation decreased from 0.99 to 0.41 m in the case of the maximum flow discharge. Consequently, automatic calibration can calibrate the model with lower error in both flow discharges. The different Manning coefficient of each reach was computed and produced an average error of approximately 4 cm and less than 7 cm between the field and simulated water elevation at each observation point considering both flow discharges of the minimum and maximum flow discharges.

5.3. Effect of expected decrease in flow discharges on flow hydrodynamics

While comparing the effect of the expected decrease in flow discharges on the flow hydrodynamics, high differences of the water elevations and flow velocities were observed. Fig. 7 and Fig. 8 compare the water elevations and flow velocities, respectively at different locations near the centerline along the reach (the chosen points are approximately 10 km spaced) under the effect of both flow discharges. It can be seen from Fig. 7 that the water elevation decreased by approximately 3.35 m to 2.05 m while the flow discharge decreased from 2560 to 685 m^3/s. Moreover, the flow velocity, as shown in Fig. 8, decreased to, approximately, its half value or less with the decrease in flow discharges, which means more residence time of pollution.

5.4. Residence time

The flow discharge in the 3rd reach of the Nile River ranges between 609 m^3/s to 2645 m^3/s. The residence time of any tracer changes with this wide range of flow discharges. In this regard, the residence times for 36 flow discharges, as indicated in Fig. 2, were

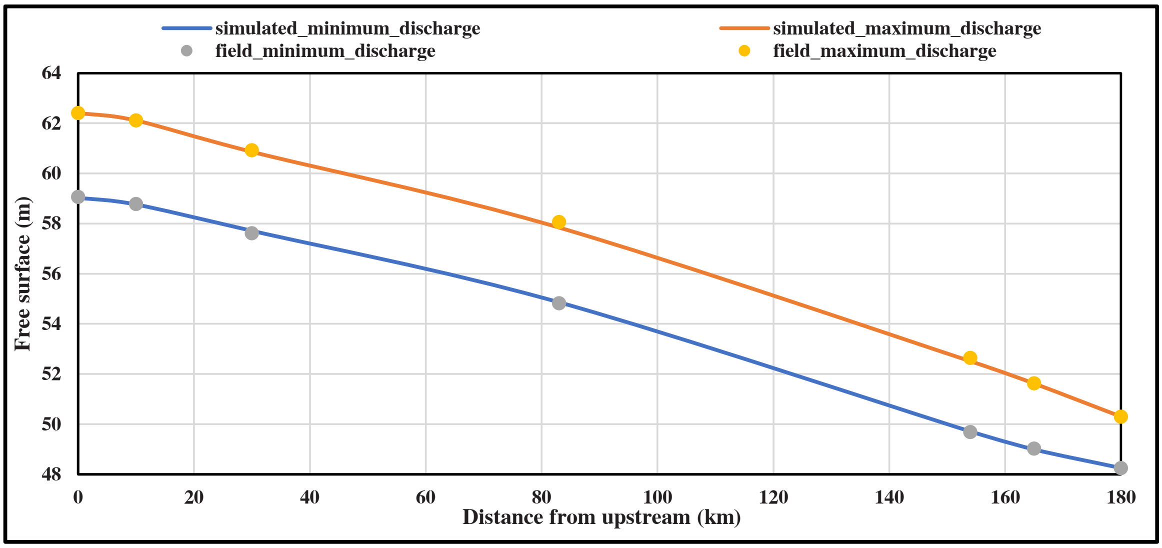

Fig. 7. Comparison between the simulated and the field free surface elevation under the effect of the minimum and the maximum flow discharge.

Table 4
Absolute variation (m) between the simulated and field water depths under the effect of both the minimum and the maximum flow discharges using the automatically calibrated Manning coefficients.

	0 km	10 km	30 km	83 km	154 km	165	sum
Min. Q	0.03	0.02	0.1	0.04	0.03	0.03	0.25 m
Max. Q	0.00	0.00	0.06	0.22	0.13	0.0	0.41 m

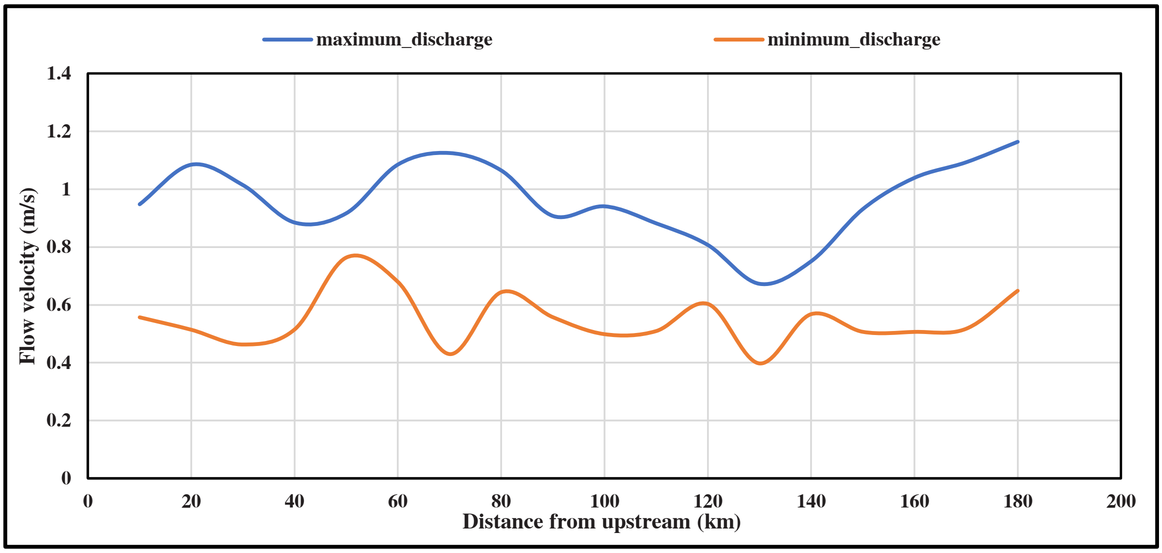

Fig. 8. Comparison between the flow velocities at different locations near the centerline along the reach (approximately 10 km spaced) under the effect of the minimum and maximum flow discharges.

examined. Firstly, the simulation using each flow discharge continued until the steady state was reached. Afterward, the polluted water was injected for only 1 day with a tracer concertation of 100 mg/l. Fig. 9 shows the simulation of tracer concentration at both the maximum flow discharge of 2645 m^3/s and the minimum flow discharge of 609 m^3/s. It can be seen from Fig. 9 that the tracer began to leave the domain after 46 hours in case of maximum discharge and 75 hours in case of minimum discharge. Also, the residence times were calculated to be 72 and 125 hours in case of the maximum and minimum flow, respectively.

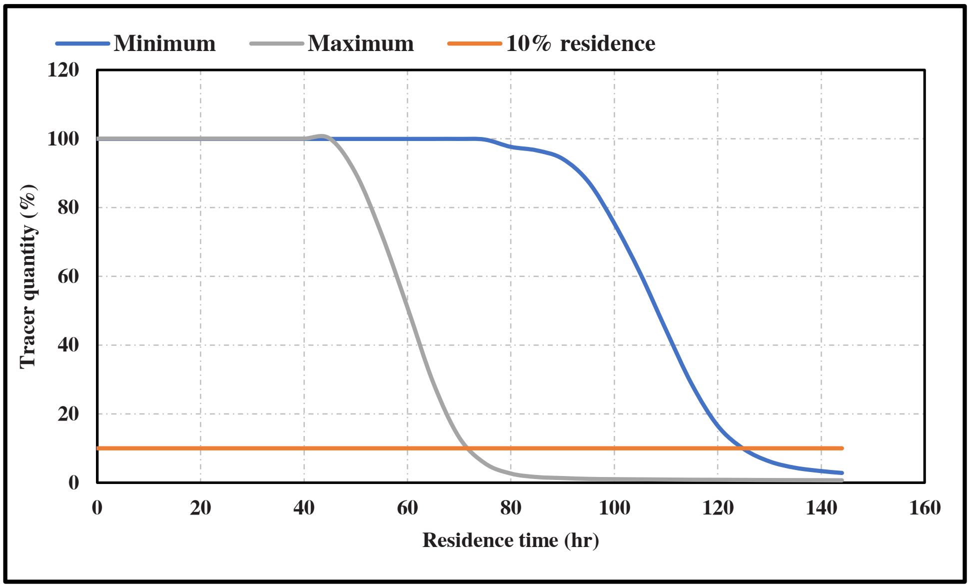

Fig. 9. Simulation of tracer concentration at both the maximum flow discharge and the minimum flow discharge of 609 m^3/s.

5.4.1. Relation between residence time and flow discharge

The values of the computed residence time for the different flow discharges (36 case studies) are shown in Fig. 10. As shown in the figure, the residence time of the 3rd reach of the Nile River can be estimated as a function of the flow discharge in the reach with a correlation coefficient of approximately 0.95.

Afterward, the residence time for each 20 km section in the domain was calculated after an injection of tracer equals 100 mg/l for only 1 hour. The residence time was computed to equal 14 hours in the 2nd section, which produced the lowest residence time, while the 6th section got rid of the tracer in more time, which equals 19 hours. It can be concluded that the residence time not only depends on flow discharge, but the Manning coefficient and the gameography also affect the residence time.

6. Discussion

A hydrodynamic and tracer transport model has been set up to simulate the 3rd reach of the Nile River in Egypt for a length of 180 km using HEC-RAS 1D and TELEMAC-2D models. It was found that the same Manning coefficient for the whole domain of 180 km with any flow discharge is misleading. This result matches with (Samir et al., 2019), who calibrated Manning coefficient along the four reaches of the Nile considering the high, average and low flow discharges during the year and divided the Nile into small reaches having different Manning coefficients. Also, it was observed that HEC-RAS 1D model produced optimum Manning coefficient more than the TELEMAC-2D optimum Manning coefficient by approximately 23 %. This conclusion matches with previous study by (Bratton and Allison, 2017), who found a 1D model required Manning coefficient 25–34 % higher than the 2D model to achieve the same calibration results. The reason for the larger Manning coefficients is because the flow velocities are averaged over the entire overbank region of each 1D cross section while the velocities are calculated for each grid cell of the 2D model. This indicates that 1D model may give relatively lower flow velocities than field results, which may be affected by the complexity of the river, the large number of bends, angles of bends and more assumptions of 1D models than 2D models. Changes in flow velocities may produce more uncertainties in model results, especially for calculations of the travel time of contamination or water quality investigations.

Afterward, an automatic calibration technique was applied using the TELEMAC-2D model by dividing the reach into 6 sections having different Manning coefficients. The Dual-Annealing optimization method, which was used for the first time to calibrate the hydrodynamics of water systems, including rivers, was applied using an HPC cluster to achieve less errors in low computational time. The automatically calibrated model could produce an average error of approximately 4 cm and less than 7 cm between the field and simulated water elevation at each observation point considering both flow discharges of the minimum and maximum flow discharges. Moreover, while comparing with manual calibration, automatic calibration could get low error in low computation time.

Finally, the tracer transport process was simulated using the TELEMAC-2D model. Different pollution incidents negatively affected the drinking water quality for millions of people in the past, without intensive research investigations. Such pollution incidents happened and will happen in the future. In this regard, discussing their effects and calculations of their residence time in the receiving water is a must. Herein in this work, the residence time of the tracer (pollution) was computed under the effect of different flow discharges. 36 flow discharges were applied in which the minimum, average and maximum flow discharge of each month during the years 2000–2018 were computed. The residence time was calculated as the time required to get rid of 90 % of the tracer in the domain, as discussed by (Abouelsaad et al., 2022b; Matta et al., 2016). It ranged between 72 and 125 hours depending on the flow discharge. It was found also that there is a high relation between the flow discharge and the residence time of the tracer, which produced a correlation coefficient of approximately 95 %. Afterwards, the residence time was calculated for each 20 km of the 3rd reach of the Nile River. The residence time of a tracer injected for only 1 hour ranged between 14 hours and 19 hours according to the studied section concluding that the residence time not only differs with the flow discharge but also changes in each reach of the domain according to different Manning values and gameography.

7. Limitations and recommendations

In this section, the research's limitations and recommendations for future investigations with regard to the Nile River's flow hydrodynamics issue are discussed as follows:

- The creation of the Nile River's 2D mesh was a difficult undertaking. There were 721 cross sections of the Nile River with a spacing of 250 m between each bottom elevation available. A significantly more precise mesh would need too much computation time, even on HPC, so a mesh resolution of roughly 18 m between nodes with a total of about 850,000 nodes and 1700,00 elements was selected. On the other hand, particularly in low flow circumstances, distinct locations could not be correctly interpolated and the water flow ceased. This meant that manually fine-tuning the mesh beside islands and in regions with significant variations in bottom elevations was essential.
- The model was calibrated in both summer and winter of the year 2018, however validation for other years was not carried out so far. Recently observed decreases in flow discharge could be used to validate the model's performance in different flow discharge scenarios of the predicted low discharge future scenarios.
- Flow hydrodynamics can be completely calibrated using the main two variables: water depths and the corresponding flow velocities. In this study, data about the water depths only were available and used for automatic calibration. On the other hand, the flow velocities can only be checked using ranges of the flow velocities mentioned in earlier literature studies for the Nile. Data about the flow velocity would enhance the flow hydrodynamicś calibration of the river. In this regard, in future studies, field

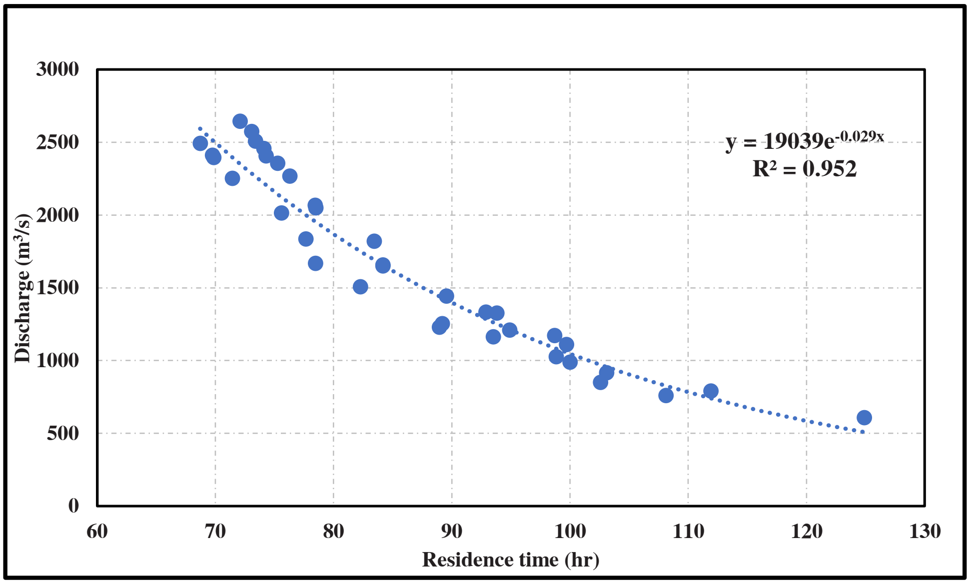

Fig. 10. Simulated residence time for the 36 cases studied considering different flow discharges during the year and the equation of the relation between the flow discharge and the residence time.

investigations of the flow velocities with water depths can enhance automatic optimization application using both variables for a better insight into the flow hydrodynamics calibration of Nile River.

– For the automatic calibration of the flow hydrodynamics, absolute variation between simulated and field water depths were selected as the objective function. Other objective functions, like Kling-Gupta efficiency (KGE) or Nash-Sutcliffe efficiency (NSE), could be used to potentially obtain a more accurate calibration in fewer trials.

8. Conclusion

This work discussed one of the most vital world water resources around the world with a precise investigation of its hydrodynamics and the repeatedly pollution incidents comparing both 1D and 2D modelling of rivers. A hydrodynamic and tracer transport model has been set up to simulate the 3rd reach of the Nile River in Egypt for a length of 180 km bounded by Naga Hammadi barrage and Asyut barrage by comparing between HEC-RAS 1D and TELEMAC-2D models. Also, a first application of an automatic optimization approach for calibrating the flow water depths using different Manning coefficients. Finally, the successful optimized model was applied to discuss the pollution incidents in the river. The principal results of the hydrodynamics and tracer transport modeling are concluded in the following:

1. TELEMAC-2D gave less errors than 1D model.
2. The Dual-Annealing optimization method could automatically calibrate the water depths using different Manning coefficients in different reaches of the Nile River in low computation time and less error without the need of expert knowledge.
3. The residence time of pollution was calculated and ranged between 72 and 125 hours depending on the flow discharge with a correlation coefficient of approximately 95 %. Also, the residence time changes in each reach of the domain according to different Manning values and gameography.

Declarations

none

Ethical approval

Not applicable.

Consent to participate and consent to publish

All authors agreed to participate and to publish this work.

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Reinhard Hinkelmann: Writing – review & editing, Conceptualization. **Mohie Omar:** Writing – review & editing. **Aziz Hassan:** Software. **Omnia Abouelsaad:** Writing – original draft, Software, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that has been used is confidential.

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