JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535
Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2026.156059
2026, No. 68 (I–III): 1–16

Novel mathematical model for long-term hydrodynamic evolution of sediment transport and its impact on meandering geometry

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RECEIVED 11.09.2025 ACCEPTED 30.12.2025 AVAILABLE ONLINE 02.01.2026

Abstract: This study presents a two-dimensional novel mathematical model to investigate the long-term evolution of sediment transport and meander migration in a low-gradient alluvial reach. The model integrates Saint-Venant shallow water equations and Exner sediment continuity equation with an empirical bank erosion module based on excess shear stress. Historical reach centrelines (2000–2024) from Landsat imagery and advanced spaceborne thermal emission and reflection radiometer digital elevation models (ASTER DEMs) were used to calibrate and validate the model against observed planform changes. Model calibration involved adjustment of hydraulic roughness (n = 0.035–0.045), sediment transport coefficients and erosion thresholds. Validation yielded strong agreement with observed data (Nash–Sutcliffe efficiency (NSE) = 0.82, root mean square error ($RMSE$) = 5.4 m, coefficient of determination (R^2) = 0.89). The simulations of future scenarios (2025–2100) showed that there are morphological changes that are quantifiable such as the increase in the meander wavelength (12%), sinuosity (9%), and the lateral migration rates up to 3.7 $m \cdot y^{-1}$ with intensified flow and reduced sediment supply. Sensitivity analysis confirmed high responsiveness of channel shape to changes in slope, discharge and bank erodibility. Results suggest downstream migration and localised bank retreat are likely under climate and land-use change impacts, with implications for infrastructure planning and river management. The model provides a robust tool for predicting river morphological evolution and supports sustainable decision-making.

Keywords: hydro-geomorphology, mathematical model, meander migration, river morphodynamics, sediment transport

INTRODUCTION

Rivers are dynamic geomorphic systems that continuously evolve in response to hydrodynamic forces, sediment transport and boundary interactions. Among them, meandering rivers exhibit lateral migration and bank erosion that reshape floodplains, influence sediment budgets and alter ecological connectivity (Bishwakarma *et al.*, 2025). Understanding these morphodynamic processes is essential for effective river management, infrastructure protection and flood risk mitigation, particularly in basins where both natural hydrological variability and anthropogenic interventions interact (Alsultani, Karim and Khassaf, 2025; Nigam, 2025).

The Euphrates River is among the most important transboundary rivers in the Middle East which has experienced great hydrological and geomorphological changes over the last decades. The Shatt Al-Hilla reach, in central Iraq, stands out as a particularly susceptible location because of the low gradient alluvial environment, fine-grained erodible banks and reliance on upstream flow of discharges in a cascade of dams in Turkey and Syria. These dams in combination with the rising climatic stressors have altered the natural flow and sediment regimes of the Euphrates River system. Flows of the annual, reduced sediment loads and extended dry seasons have also been found to modify the natural meandering and led to local channel instability and changed bank erosion (Iacobucci, 2021; Al-Khafaji and Al-Merib, 2024).

Other than that, it is expected that the climate change in Iraq will increase substantially in terms of temperature, evapotranspiration and extreme variability of flow that would further change hydraulic and sediment regimes of rivers in the area. The sustainability of agriculture, flood management, and structural integrity of the infrastructures of Babylon Province are extremely problematic due to the influence of these compounded stressors because the Shatt Al-Hilla reach is a significant water and sediment transportation route in Babylon Province. Therefore, it is significant to establish how well this reach can adapt the morphological response to the flow and sediment regime variation in order to plan adaptive and sustainable management strategies.

The latest techniques of numerical morphodynamic modelling have performed a significant role in improving the potential to simulate the evolution of channels under varying boundary conditions (Pant *et al.*, 2025). In combination with remote sensing and geographic information system (GIS) data, such tools as FLOW-3D, MIKE21 and Delft3D can be applicable to simulate erosion, deposition and meander evolution at high-resolution decadent to centennial periods (Anees, 2024; Ansarifard *et al.*, 2024). Such approaches are particularly valuable in data-scarce regions like Iraq, where long-term monitoring networks are limited, and the combined influence of climate change, dam regulation and land-use transformations is expected to intensify future morphological adjustments (Abduljaleel, 2020; Greenberg and Ganti, 2024; Hooke, 2022).

Globally, numerous studies have advanced the understanding of meander evolution and channel migration mechanisms (Howard, 2009; Benson, 2020; Song, Xu and Bai, 2024; Yang *et al.*, 2024; Pradhan and Khatua, 2025a; Pradhan and Khatua, 2025b). However, comparatively few investigations have focused on the Euphrates River system within Iraq, where semi-arid hydrology, sediment scarcity and human-induced flow alterations create distinctive morphodynamic behaviour. Notable regional efforts include Alsultani *et al.* (2025), examined planform change using multi-temporal satellite imagery and Al-Khafaji and Al-Merib (2024), who assessed sediment transport and channel response at the Shatt Al-Hilla reach. Similarly, Al-Fahdawi (2009) and Jassim, Mohamed and Abdullah (2023) explored localised meandering processes, yet these studies often lack integrated, process-based frameworks capable of quantifying long-term morphological evolution under multiple future scenarios.

Accordingly, this study addresses the identified research gap by developing a two-dimensional morphodynamic model that explicitly couples hydrodynamics, sediment continuity and bank erosion processes to simulate the long-term evolution of the Shatt Al-Hilla reach of the Euphrates River. The model integrates remotely sensed planform data (2000–2024) for calibration and validation and projects channel evolution under future scenarios (2025–2100) incorporating climate change, upstream regulation and land-use alterations.

The main objectives of the study are to: 1) quantify projected changes in channel geometry, including width, meander wavelength and sinuosity, 2) evaluate sediment transport pathways and spatial patterns of erosion and deposition, 3) assess the sensitivity of meander morphology to variations in slope, discharge and sediment supply, 4) propose adaptation and mitigation strategies for river management under changing environmental conditions.

This study can be considered a new data-driven model of the prediction of river morphological evolution in semi-arid, regulated systems by combining advanced modelling with scenario-based simulations. The results will be used to make evidence-based management decisions, resilience of the infrastructure and sustainable development planning in the Euphrates River basin.

MATERIALS AND METHODS

GEOGRAPHIC AND HYDROLOGIC CHARACTERISTICS

The Shatt Al-Hilla River is a significant distributary branch of the Euphrates River, located in the central part of Iraq. It originates from the Hindiya Barrage, located approximately 20 km south of the city of Al-Hindiya and flows southeast through Babylon Province before converging with the Shatt Al-Diwaniyah River further downstream, as presented in Figure 1. The river traverses a predominantly lowland alluvial plain, characterised by gentle gradients and extensive agricultural use along its banks (Al-Dabbas, 2024).

The average length of the Shatt Al-Hilla River is approximately 120 km, with a channel width ranging between 40 and 120 m depending on location and seasonal flow conditions. It serves many irrigation programs and is influential on agricultural output and water provision to the local populations (Shehab and Riyadh, 2025). A system of barrages, regulators and mini pumping stations hydraulically controls the river, having an impact on regimes of flows and the characteristics of sediment transport.

Riverbed consists of fine-grained alluvial sediments and it consists of silts, clays and fine sands and occasionally coarser deposits are noted around artificial structures or high-energy areas. The riverbanks are not cohesive and subject to erosion of the river when it is in high discharge state resulting in the morphological instability and the channel migration on the sides.

CLIMATIC CONDITIONS AND CATCHMENT DETAILS

The Shatt Al-Hilla River is found on the semi-arid arid climate area of central Iraq and rainfall is concentrated on a seasonal basis between the months of November and April (Abaas and Shamkhi, 2025). The rainfall in the area ranges between 100 and 200 mm on average and interannual variance on rainfall is high. Hot and dry summers, when it is over 45°C and cold winters, between 5 and 20°C (Alsaadi and Al-Thamiry, 2022).

The Shatt Al-Hilla has a catchment area mostly based on the larger Euphrates River Basin that extends to Turkey and Syria on

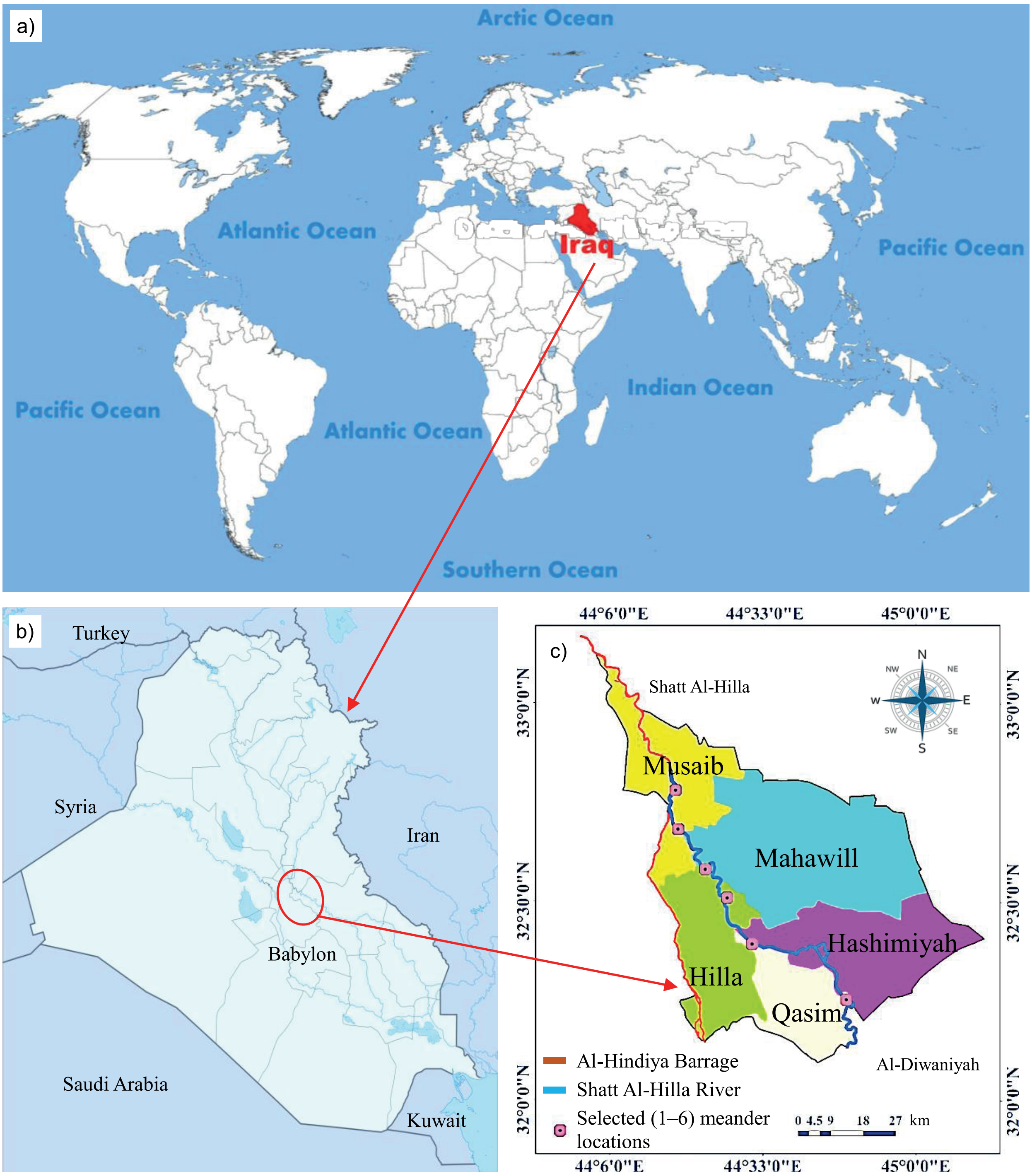

Fig. 1. Selected case study area with key locations and historical centrelines within: a) world, b) Iraq, c) the Euphrates River system; source: own elaboration

its upper reaches. Although the area covered by the immediate catchment of Shatt Al-Hilla is quite small, it is fed by the upstream Hindiya Barrage that regulates its discharges according to the needs of agriculture and operation.

Due to limited rainfall and high evapotranspiration rates, the river's discharge is heavily influenced by upstream reservoir releases and canal diversions. This results in a highly managed hydrological regime with reduced natural variability, affecting sediment transport capacity and the natural evolution of channel morphology.

HISTORICAL BEHAVIOR AND MORPHOLOGICAL CHANGES

Historically, the Shatt Al-Hilla River has displayed dynamic meandering behaviour, particularly in unregulated or less confined sections (Noori, 2024). Archival maps, satellite images and field surveys over the past several decades indicate that the river has undergone considerable planform evolution, with evident lateral migration, cutoff formation and bankline shifts.

Since the mid-20th century, anthropogenic interventions, including the construction of barrages (e.g., Al-Hilla Barrage) and embankments, have modified the natural flow and sediment regime of the river (Islam *et al*., 2020; Omran and Almansori, 2024). These changes have shifted the ability of the river to naturally realign its planform which has caused sedimentation of some reach and constriction or avulsion of others.

According to the studies conducted over the last 40 years, remote sensorial and geographic information system (GIS)-based studies have demonstrated the progressive changes in the river sinuosity and meander wavelength in response to the varying flow conditions and other local interventions (Langat, Kumar and Koech, 2019; Tomsett and Leyland, 2019; Sun *et al*., 2025). In some of the reaches, the lateral migration of the channel over a distance of over 100 m has shown that there are active fluvial processes and that there is continued erosion of the banks.

PREVIOUS OBSERVATIONS OF SEDIMENTATION AND CHANNEL MIGRATION

The existence of fine cohesive materials suspended in the water and quite low levels of transport of bedloads at moderate flow levels have been verified by field observations and sediment sampling campaigns. Nevertheless, in peak events or surges in operational flows of the Hindiya Barrage, considerable sediment mobilisation takes place resulting in aggradation in low velocity areas and erosion at outer meander bends (Ahmed and Mohammed, 2025).

Bank erosion is also active especially in soils that are non-cohesive or those that are poorly vegetated. Livestock actions, agricultural intrusions and alteration of channels which alter the flow alignment contribute to the erosional process (Marteau *et al*., 2018; Mandal and Majumdar, 2024). Longitudinal profiles of the river reveal alternate areas of sediment deposition and scouring, which play a role in the movements of meander crests and the lengthening of meander loops.

Albeit without the extensive coverage of previous studies, localised problems of sedimentation close to hydraulic structures have been documented and the modelling of predictive models to understand morphology changes in the long term has been emphasised (Rather *et al*., 2023; Zhang and Guo, 2025). The inability to monitor the field in real time has long been the constraint of comprehensive evaluations, which is why the importance of using remote sensing and mathematical modelling methods to estimate river evolution during decadal periods cannot be overestimated.

DATA COLLECTION AND PROCESSING

The reliability and accuracy of any mathematical model for sediment transport and channel evolution are highly dependent on the quality and comprehensiveness of the input data. This study integrates remote sensing datasets, field measurements and official hydrologic records to develop a robust framework for simulating the long-term evolution of the Shatt Al-Hilla River's meandering pattern.

SOURCES OF DATA

A multi-temporal dataset of cloud-free Landsat satellite images (Landsat 5 TM, Landsat 7 ETM+ and Landsat 8/9 OLI) was acquired from the United States geological survey earth-explorer portal (https://earthexplorer.usgs.gov/). The temporal range spans 2000 to 2025, with images selected primarily from dry-season months (June–September) to minimise cloud interference and high river stage effects. All images have a 30 m spatial resolution. Preprocessing included radiometric calibration, atmospheric correction and geometric rectification to ensure consistency across years. River centrelines and channel boundaries were digitised for each time step, and successive images were compared to quantify planform changes, identifying zones of erosion, deposition and meander migration. The accuracy of digitised river outlines was assessed using high-resolution Google Earth imagery and local surveyed checkpoints, yielding an estimated positional accuracy horizontal error range from −5 to +5 m.

Landsat imagery and advanced spaceborne thermal emission and reflection radiometer digital elevation models (ASTER DEMs) global digital elevation model (GDEM v3), also at 30 m resolution, were employed to extract elevation profiles, longitudinal slopes and watershed boundaries. Elevation data were preprocessed to fill sinks, correct anomalies and ensure hydrological connectivity. Flow direction and accumulation maps were generated to delineate sub-catchments and determine spatial variations in river slope. Vertical accuracy was validated against surveyed elevation benchmarks provided by local authorities, showing a mean error of ±2 m. The DEM data were then integrated with river planform datasets to support hydraulic and sediment transport modelling.

Hydrological time-series data, including river discharge, water levels and seasonal flow records, were obtained from the Iraqi Ministry of Water Resources and the General Directorate for Water Resources in Babylon Province. Data from key gauging stations, particularly Hindiya Barrage (upstream) and Al-Hilla City (mid-reach), were used to estimate mean annual and peak discharges. These datasets, covering more than two decades, were used to calibrate and validate the hydrodynamic component of the model and to estimate sediment transport capacity under varying flow regimes (Saber *et al*., 2025).

Sediment sampling data were collected through field campaigns and published studies (Abduljaleel, 2020; Omran and Almansori, 2024). Sampling followed standardised protocols: suspended load samples were collected at mid-channel using depth-integrated samplers, while bedload samples were obtained using a Helley-Smith sampler at representative cross-sections. Grain size distributions were analysed in the laboratory using sieving and laser diffraction techniques to determine parameters such as d_{50} and d_{90} (median and coarse particle sizes). Total sediment loads were estimated for high-flow and low-flow conditions and in areas lacking local data, values from analogous alluvial rivers in Iraq were used. All sediment data were integrated with hydrological and remote sensing datasets to calibrate the Exner sediment continuity equation and bank erosion modules within the morphodynamic model.

Spatial and temporal resolutions of the integrated dataset were as follows: 30 m horizontal resolution for remote sensing and DEM data, daily to monthly temporal resolution for hydrologic data and high-resolution point measurements for sediment sampling. This comprehensive dataset ensures reproducibility and supports robust modelling of long-term channel evolution and meander dynamics in the Shatt Al-Hilla River.

GEOGRAPHIC INFORMATION SYSTEM TECHNIQUES FOR MEANDER GEOMETRY EXTRACTION

The ArcGIS Pro and QGIS software were used to perform the spatial analysis. Landsat images had their river centrelines digitised manually, and then year by year, the centrelines were adjusted so that they aligned with the visible channel features (Ansarifard *et al.*, 2024). A set of meander geometry parameters were obtained using these centrelines:
– river width: measured as the perpendicular distance between left and right bank-lines at equidistant transects;
– meander wavelength (λ): defined as the distance between two successive inflection points of the river centreline;
– sinuosity (S): calculated as the ratio of channel length to valley length over defined reaches;
– channel slope: derived from advanced spaceborne thermal emission and reflection radiometer digital elevation models (ASTER DEMs) using slope calculation tools and cross-validated with hydraulic grade lines from field surveys;
– curvature and migration rate: measured by analysing shifts in centreline positions over time, quantifying lateral migration.

These spatial parameters were organised into a geodatabase for subsequent integration into the hydrodynamic and sediment transport models (Islam *et al.*, 2020).

PREPROCESSING STEPS AND ACCURACY ASSESSMENT

A number of preprocessing operations were conducted in order to guarantee data consistency and compatibility.
1. The Landsat images were orthorectified and atmospherically corrected in the Landsat ecosystem disturbance adaptive processing system (LEDAPS).
2. Digital elevation model (DEM) smoothing: hydrological conditioning techniques (e.g., fill sinks and flow direction tools) were applied to digital elevation models of advanced spaceborne thermal emission and reflection radiometers (ASTER DEMs) to eliminate sinkholes and false ridges.
3. Projection and resampling: all the spatial data were transformed to one coordinate system (universal transverse Mercator zone 38N world geodetic system (WGS) 84) and transferred the data to a standard spatial resolution (30 m).
4. Measures of accuracy: the geometric accuracy of river centrelines and bank-lines were assessed using assessment of accuracy points taken out in the field (at field visits). Root mean square errors (*RMSE*) between digitised features and global positioning system (GPS) points were maintained to less than 10 m. The validation of the elevation data was conducted using surveyed cross-sections and spot heights.

Through these, there was so much spatial and time precision, which ensured that the input information could be applied in simulating long-term meandering evolution and sediment dynamics of the Shatt Al-Hilla River.

MODEL DEVELOPMENT

A sound two-dimensional (2D) mathematical model is constructed in order to model the complex interactions existing between river hydrodynamics, sediment transport and bank erosion occurring over long durations of time. The model is to be used to capture the temporal and spatial evolution of the planform geometry of the Shatt Al-Hilla River which is undergoing the constant transformation due to the fluvial processes in the low-gradient environment.

SELECTION OF MODELLING FRAMEWORK

The modelling scheme is based on a two-dimensional (2D) depth-average finite element model that offers sensible trade-offs between the computational and spatial resolution. Latex, the 2D approach solves the lateral variation in the velocity of the flowing water, height of the water surface, transportation of water sediments and the distribution of shear stress that are significant in the modelling of meandering dynamics.

A structured mesh was developed based on triangular elements that conforms to the geometry of the river and makes the mesh numerically stable at bends and confluences. The hydrodynamic solver is an approximation of the Saint-Venant equations (shallow water equations) and the sediment transport solver contains the Exner equation of bed evolution. The process-based and empirical approach to erosion of the banks is adjusted to the specific aspect of the Shatt Al-Hilla River.

GOVERNING EQUATIONS

The two-dimensional (2D) depth-averaged shallow water Saint-Venant equations describe the conservation of mass and momentum in the horizontal plane (El Hassanieh, 2023; Joudah *et al.*, 2024):
– continuity:

$$\frac{\partial h}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}=0 \tag{1}$$

where: ∂ = partial derivative operator, t = time (s), h = water depth (m), u, v = depth-averaged velocity components in x and y directions (m·s^{-1});
– momentum equations (in x and y directions):

$$\frac{\partial (hu)}{\partial t}+\frac{\partial (hu^2)}{\partial x}+\frac{\partial (huv)}{\partial y}=-gh\frac{\partial \eta}{\partial x}+\frac{\tau_{bx}}{\rho} \tag{2}$$

$$\frac{\partial (hv)}{\partial t}+\frac{\partial (huv)}{\partial x}+\frac{\partial (hv^2)}{\partial y}=-gh\frac{\partial \eta}{\partial y}+\frac{\tau_{by}}{\rho} \tag{3}$$

where: η = water surface elevation (m), g = gravitational acceleration (9.81 m·s^{-2}), ρ = water density (kg·m^{-3}), τ_{bx}, τ_{by} = bed shear stresses in x and y directions (N·m^{-2}).

The Exner equation governs the conservation of bed material (An *et al.*, 2018):

$$(1-\lambda_P)\frac{\partial z_b}{\partial t}+\frac{\partial q_{sx}}{\partial x}+\frac{\partial q_{sy}}{\partial y}=0 \tag{4}$$

where: λ_p = bed porosity (typically 0.35–0.45), z_b = bed elevation (m), ∂q_{sx}, ∂q_{sy} = sediment transport rates in x and y directions (m^2·s^{-1}).

The total sediment transport rate is typically decomposed into bedload and suspended load components. A suitable transport formula, such as Engelund–Hansen or van Rijn, is used depending on the grain size and flow regime of the river.

Bank erosion is incorporated using a hybrid approach that includes both empirical and process-based methods.

1. Ikeda model (meander migration based on channel curvature). The Ikeda, Parker and Sawai (1981) model relates the rate of lateral migration (M) to local curvature (κ) and excess near-bank velocity:

$$M = E \cdot U \cdot \kappa \tag{5}$$

where: M = migration rate (m·y^{-1}), E = erosion coefficient (calibrated), U = local flow velocity (m·s^{-1}), κ = curvature (1/R, where R is the radius of curvature).

2. Excess shear stress model (process-based bank erosion). This model defines the rate of erosion as a function of the applied boundary shear stress exceeding a critical threshold (Inoue, Mishra and Parker, 2021):

$$\varepsilon = k_d(\tau_b - \tau_c)^a \text{ for } \tau_b > \tau_c \tag{6}$$

where: ε = erosion rate (m·s^{-1}), k_d = erodibility coefficient (m^3·N·s^{-1}), τ_b = applied shear stress (Pa), τ_c = critical shear stress (Pa), a = empirical exponent (typically between 1 and 2).

MODEL ASSUMPTIONS AND LIMITATIONS

To simplify the complex natural processes into a form suitable for computational modelling, several assumptions were made. First, the river is represented as a two-dimensional, depth-averaged system, which means that vertical velocity profiles are not explicitly resolved within the model. This assumption helps reduce computational complexity while maintaining a realistic portrayal of flow behaviour. Additionally, the bed material is considered non-cohesive, homogeneous and well-mixed throughout the modelled reach. This simplification results in the calculation of the transport of sediments becoming easier and causes less variability due to the uneven conditions of the substrates.

The effect to flow resistance and bank stability by vegetation is not directly modelled. Instead, these effects are introduced in with calibrated roughness coefficients that are proxy values to indicate the increased resistance that is normally imposed by vegetation.

The model fails to reflect the processes of bank failures such as mass wasting or piping. It is assumed that the erosion processes are primarily hydraulic as the shear stresses, which are due to flowing water on the boundaries of the channels are fulfilled. Moreover, the lateral channel migration of rivers is regarded as being a continuous process, which is simply determined by the local hydrodynamic conditions. Human activities External processes such as dam operation or unexpected anthropogenic fluctuation are not included in this system.

Despite such simplifications, the model is very powerful and reasonable in the search of long-term morphological patterns particularly the meander evolution of average hydrologic condition.

COUPLING BETWEEN HYDRODYNAMICS AND SEDIMENT TRANSPORT

Both of the modules are hydrodynamic and sediment transport modules that are coupled and solved iteratively on a time step basis. The coupling mechanism works in the following way.

1. Flow variables (h, u, v) are computed from the Saint-Venant equations.
2. These flow fields are used to evaluate bed shear stresses and compute sediment transport rates.
3. The Exner equation is used to update the bed elevation.
4. Updated bed profiles influence water depth and flow distribution in the next iteration.

This coupling ensures a dynamic feedback mechanism between flow, erosion and morphology, allowing the model to simulate realistic river meandering and sediment redistribution patterns. In Figure 2, the steps of the current proposed model are shown.

MODEL CALIBRATION AND VALIDATION

The model calibration process relies on historical meander data obtained from satellite imagery, such as Landsat and other remote sensing datasets. These sources provide high-resolution spatial data that capture changes in river geometry over time. Key features such as meander wavelength, channel sinuosity and lateral migration patterns are extracted from the imagery and used to inform and refine the model parameters to ensure its reliability in simulating real-world river behaviour.

Calibration process consists of a number of processes which are important:

- a suitable time is selected in which the calibration is to be done, preferably covering a range of years or decades; this long time interval will enable the natural variability of river geometry and sediment transport to be captured, and provides a more comprehensive dataset with which to compare it;
- the model creates a river planform that is then associated with the geometry that has been observed through satellite images and fieldwork measurements; this involves examining the differences in meander forms, channel location and migration cycles to determine how well the model represents the real-world conditions;
- based on the outcomes of the comparison, model parameters of interest, e.g., flow resistances (roughness coefficients), bedload and suspended load of the river, critical shear stress levels at which erosion occurs are adjusted systematically, and this is repeated until the discrepancies between the simulated and observed river geometries are reduced, and, consequently, the predictive ability of the model is enhanced.

In this method of calibration, the model is adjusted to suit the dynamics unique to the study area, and it is more likely to predict the morphological development over long periods and under changing hydrologic conditions.

The calibration procedure will entail the adjustment of some important model parameters, which affect hydrodynamics, predictions of sediment transport and bank erosion.

The coefficient of roughness (n) is used to explain the resistance to flow caused by the riverbed and its banks, and the flow velocity and the rate of sediment transport. Usually modified to suit experienced flow velocities or water surface levels.

These parameters are known as sediment transport coefficients (Engelund–Hansen parameters, K_b), which are the parameters that control the sediment transport capacity and are relevant to the changes in the movement of sediment over time (Li *et al.*, 2023).

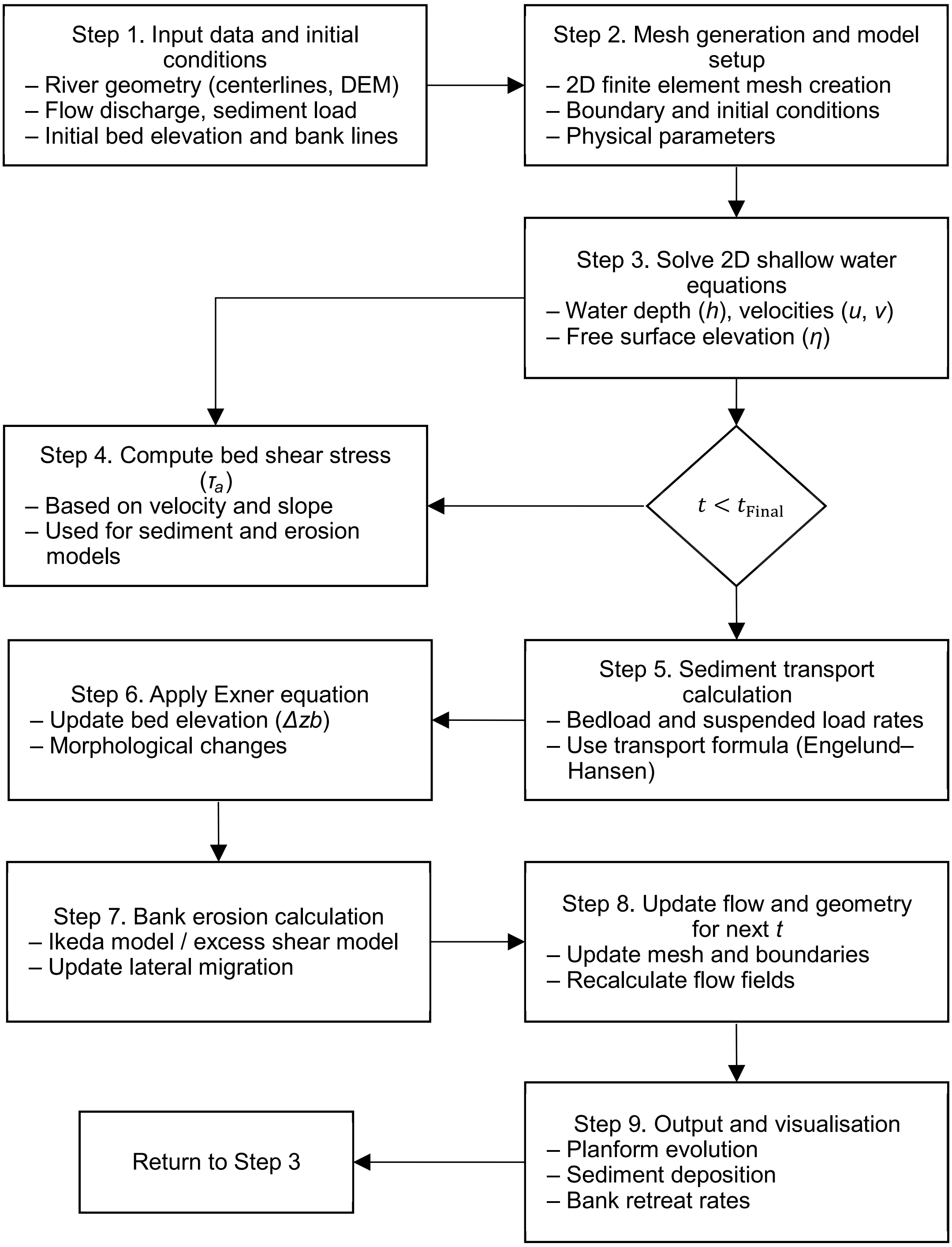

Fig. 2. Methodology of the current proposed model; DEM = digital elevation model, 2D = two-dimensional, t = simulation time, t_{Final} = final (end) time of the simulation; source: own elaboration

$$Q_s = K_b \cdot \tau_b{}^2 \tag{7}$$

where: Q_s = sediment transport rate (kg·s^{-1}), K_b = transport coefficient, τ_b = bed shear stress (Pa).

Critical shear stress (τ_{cr}) needed to get the erosion on again is set depending on the observed bank erosion rates. The model is calibrated with a comparison between simulated bank retreat data with the observed data of lateral migration.

After calibration of the model, it is then tested using independent datasets that were not used in the process of calibration. Such validation is significant to confirm the reliability and predictive accuracy of the model in various conditions. The validation datasets are measured flow data, sediment transport data, and morphological change data.

Measured flow data are the series of time of river discharge measured in local hydrological monitoring stations. Such records are employed in evaluating the degree to which the model predicts the flow behaviour with time. Sediment transport data contain records of sediment loads and size distributions, usually determined by sediment sampling or sediment transport monitoring stations. These data may be used to validate the model on the dynamics of sediments in it in terms of mobility of both bedload and suspended load.

The data of morphological change gives information about the change in riverbed and bank geometry with the passage of time. This is done by field measurements or remote sensing measurements of erosion, sediment deposition and channel movement. The model is put to test in order to reproduce the morphological evolution of the real world by comparing the output of the model with the observed morphological evolution.

Validation procedure includes the strict comparison of the results of simulation and observations with the aim to evaluate the performance of the model in predicting the river morphology, sediment transport, and hydrodynamic behaviour. A successful validation enhances trust in the model to be used in future to conduct an assessment, plan and manage river systems.

In order to measure the level of accuracy and the performance of the model, a series of statistical indicators are used in order to compare the results of the observations and the simulation. These indicators are employed to measure both the efficiency of the model in reproducing the real-life data and to interpret any deviation of results that could be creating a mismatch on the erosion of banks.

One of the major metrics is Nash–Sutcliffe efficiency (*NSE*). It determines the similarity of the predicted values with the observed values. A positive *NSE* of 1 indicates a very high correlation i.e. a perfect fit, and a negative *NSE* indicates that the model fits badly, i.e. it is not doing any better than simply using the mean of the observed values as a predictor. The formula for *NSE* is:

$$NSE = 1 - \frac{\sum_{i=1}^{n} \left(Q_{\text{obs},\, i} - Q_{\text{sim},\, i}\right)^2}{\sum_{i=1}^{n} \left(Q_{\text{obs},\, i} - \bar{Q}_{\text{obs},\, i}\right)^2} \tag{8}$$

where: $Q_{\text{obs},\, i}$ = the observed value at time step *i*, $Q_{\text{sim},\, i}$ = the simulated value at time step *i*, $\bar{Q}_{\text{obs},\, i}$ = the mean of the observed values.

Another important measure that is used is the root mean square error (*RMSE*) which is used to determine the average size of the discrepancies between the actual and simulation values. Lower *RMSE* value is a better fit of a model.

As well, the coefficient of determination (R^2) is used to assess the share of the observed statistics that the model is able to account for. The value of R^2 that is close to 1 indicates that there is a close relationship between the observed and simulated outcomes.

Together, these statistical tools offer a wholesome evaluation of the performance of the model to achieve refinement, and more confidence in the use of the model in predicting river behaviour and sediment transport processes.

The calibration and validation results for the model, showing the comparison between the observed and simulated values for various model discharge, sediment transport and bank erosion parameters are summarised in Table 1.

The model calibration and validation results demonstrate that the model is capable of accurately simulating the flow, sediment transport and morphological changes of the Shatt Al-Hilla River. The Nash–Sutcliffe efficiency values close to 1, the low *RMSE* values and the high R^2 values indicate that the model is reliable for predicting river dynamics and meander evolution.

The results demonstrate excellent agreement across all variables, with mean flow discharge showing a near-perfect fit (*NSE* = 0.98, R^2 = 0.99, *RMSE* = 2.5 $m^3 \cdot s^{-1}$), indicating that the hydrodynamic module accurately reproduces flow dynamics. Sediment load is also well captured (*NSE* = 0.95, R^2 = 0.96), reflecting the robustness of the sediment transport formulations and calibration of transport coefficients. The morphological parameters such as meander wavelength, bank retreat rates are strongly correlated with observations (R^2 > 0.94), which proves the fact that the model is reliable in predicting the long-term channel evolution and subsequent lateral migration processes. All these results of validation give reason to believe that the integrated model framework can be highly accurate and effective instrument of simulating the hydrodynamics, the transportation and morphodynamics of sediment of the Shatt Al-Hilla River under various conditions.

SCENARIO DESIGN AND SIMULATION

To examine the morphological changes of the Shatt Al-Hilla River over a long term, a complex simulation system was developed, including a base scenario and various future scenarios including a 75 years (2025–2100) of changes. The base scenario is a combination of the current hydrodynamic and sediment transport conditions which serves as a reference point. It incorporates observed flow regimes, sediment transport, bank material characteristics and river morphology based on field information, and local hydrological records and multi-temporal Landsat information. The major morphological features such as the river width, meander wavelength, sinuosity and bank erosion rates were computed to come up with baseline conditions.

Table 1. Calibration and validation results comparing observed and simulated parameters

Parameter	Observed value (AMM)	Simulated value	Statistical indicator		
			NSE	*RMSE*	R^2
Mean flow discharge ($m^3 \cdot s^{-1}$)	250	248	0.98	2.5	0.99
Sediment load ($kg \cdot s^{-1}$)	350	340	0.95	15.2	0.96
Meander wavelength (m)	5,000	4,950	0.97	12	0.98
Bank retreat rate ($m \cdot y^{-1}$)	2.5	2.3	0.93	0.3	0.94

Explanations: AMM = annual mean measurements, *NSE* = Nash–Sutcliffe efficiency, *RMSE* = root mean square error, R^2 = coefficient of determination.
Source: own study.

Future scenarios that were aimed at exploring the impacts of climate variability, upstream water regulation and anthropogenic land use changes were shown in Table 2. The flow regime, sediment supply and bank composition were adjusted on the basis of observed trends, literature values and realistic estimates of the future values. To each scenario, consistency checks were performed in such a way that real interaction between variables takes place. The effects on river morphology, channel stability and lateral migration rates can be assessed through combined simulations to determine the cumulative effects.

This is a scenario-based method that makes the parameter adjustment to be in line with the realistic hydrological, geomorphological and anthropogenic conditions, offering a strong platform towards forecasting future river morphology. The interactions between climate variability and sediment dynamics, human interventions have shown to be complex and thus simulations continue to be a good decision-support system towards sustainable river basin management and adaptive planning in the Shatt Al-Hilla reach.

RESULTS AND DISCUSSION

CHANNEL GEOMETRY AND MEANDER MIGRATION

The morphodynamic simulation of the Shatt Al-Hilla River in the long-term depicts tremendous variations in geometry of the channel and meandering migration at different climatic and anthropogenic circumstances. These changes suggest that the river is dynamic to react to the changes in the hydrologic conditions, the supply of sediment and the land use patterns.

A scheme analysis was conducted to investigate the hydrodynamic response of the selected six distinct meander shapes under varying water depths using a two-dimensional, depth-averaged hydraulic model based on the current study proposed model, as illustrated in Figure 3.

The simulation also incorporated bank stress analysis through a soil-structure interaction framework to account for erosion and stability. Model parameters were standardised across all shapes, with water depths categorised into low (1.0 m), medium (3.0 m) and high (5.0 m) and corresponding flow velocities set at 0.5, 1.5 and 2.5 m·s^{-1}, respectively. The riverbank soil was modelled as clayey loam with an internal friction angle of 22° and cohesion of 20 kPa, while bed roughness was assumed constant with a Manning's n value of 0.03. Sediment was represented as medium

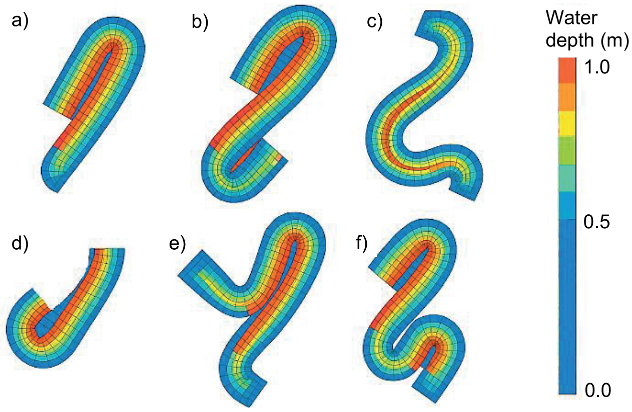

Fig. 3. Modelling scheme for meander shape analysis under variable hydraulic conditions: a) meander location 1, b) meander location 2, c) meander location 3, d) meander location 4, e) meander location 5, f) meander location 6; source: own study

sand with a median grain size (d_{50}) of 0.5 mm. Each meander configuration was subjected to these hydrodynamic conditions and the finite element mesh was adjusted to capture spatial variations in flow direction, depth distribution and channel-bed interaction for comprehensive analysis.

The long-term analysis of the compound meander from 2025 to 2100 reveals a progressive shift from a stable channel to a highly dynamic and potentially unstable system, as in Figure 4.

The meander has initially a balanced flow and sediment condition but by 2040 the upstream regulation decreases the supply of sediments which slightly changes the channel geometry. The channel incision and outer bank erosion occur in 2055 due to dry climate whereas the land use changes in 2070 enhance the channel widening and instability. The wet climate conditions by the year 2085 will advance meandering migration and deepen the curvature that will pose a great threat of cutoff. Through increasing peak flows due to urbanisation, and by 2100, the system will be on the edge of morphodynamic failure with firm signs of oxbows. In general, the meander evolution indicates the dual impact of hydrologic change and anthropogenic stressors on the river stability and channel morphology.

Under the wet climate scenario projected for 2085 and 2100, the model predicts an increase in both meander wavelength and sinuosity, along with a notable widening of the river channel. This transformation is attributed to enhanced precipitation and runoff, which elevate flow velocities and sediment transport capacity,

Table 2. Simulation scenarios, rationale and parameter adjustments

Scenario	Target variable(s)	Parameter adjustment
Base (current)	flow, sediment, bank	observed discharge, sediment load and bank composition
Wet climate (2085–2100)	flow	+20% discharge
Dry climate (2055)	flow	–15% discharge
Upstream dam (2040)	sediment	–30% sediment supply downstream
Deforestation (2070)	sediment, bank	+15% sediment, decreased cohesion
Urbanisation (2040–2055)	sediment, bank	–10% sediment, increased bank reinforcement

Source: own study.

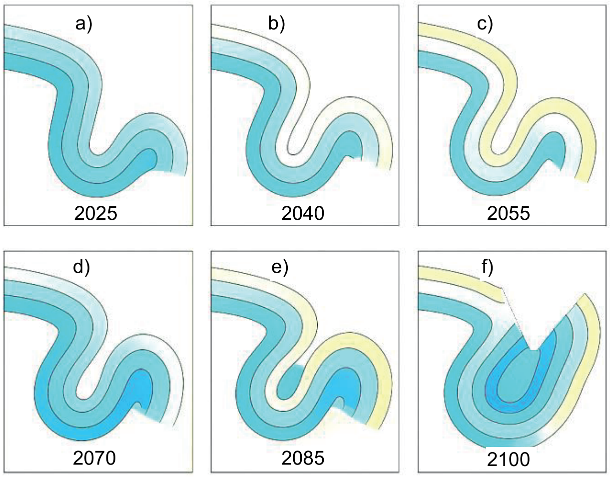

Fig. 4. Long-term morphodynamic evolution of a compound meander under changing hydrologic and anthropogenic conditions in 2025–2100: a) 2025, b) 2040. c) 2055, d) 2070, e) 2085, f) 2100; source: own study

promoting aggradation within the channel. Consequently, meander migration rates increase, driven by stronger erosive forces and lateral instability.

Conversely, the situation of a dry climate as projected in the year 2055 has a narrowing of the channel, lesser meander migration and a decreased sinuosity. These tendencies are caused by a decrease in precipitation and a decrease in energy transport, which limit the movement of sediments and stimulate the excavation of the channels. The river becomes more fixed and stable in its morphology, being able to change laterally only to a small degree.

The scenario of upstream dam (2040) illustrates the geomorphologic impacts of the reservoirs trapping of sediments. The enormous decrease in the amount of downstream sediment results in channel stabilisation, decreased meander activity and diminished rates of movement. Though the channel increases its structural stability, this is at the expense of reduced morphodynamic diversity, in the form of reduced meander wavelengths and reduced sinuosity, as demonstrated by Hasan *et al.* (2024).

The scenario of deforestation forecasted in the year 2070 presents the repercussion of loss of vegetation on the sediment processes. The surface runoff also adds the surplus sediment in the river leading to more morphological activity, broader channels, and further accelerated meander migration. This highlights the delicateness of lateral channel dynamics to changes in land use at the catchment scale.

In comparison, the urbanisation scenario projected in 2100 contributes to reduction of sediment input because of surface sealing and surface stabilisation of the banks. This means that meandering migration is very minimised and the channel takes a more fixed and regulated shape, having lower sinuosity and limited morphological adaptations. All these situations demonstrate that climate variability, sediment supply and land use interact in a complicated way in determining river morphology. In Figure 5, a comparative illustration of the projected changes in river geometry and meander migration across the modelled scenarios is presented.

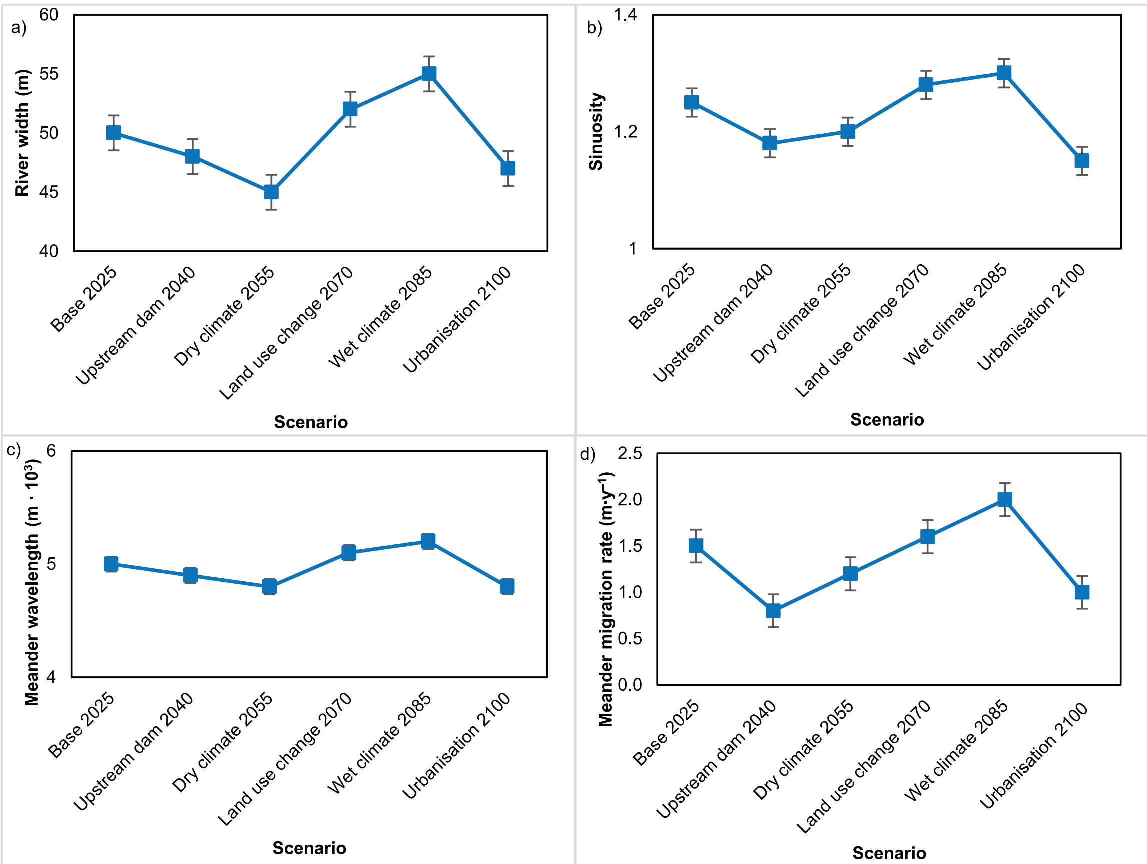

Fig. 5. Projected changes under different scenarios in channel geometry and meander migration: a) river width, b) sinuosity, c) meander wavelength, d) meander migration rate; source: own study

LONGITUDINAL AND SPATIAL TRENDS IN SEDIMENT DEPOSITION AND EROSION

Both longitudinal and spatial patterns of sediment deposition and erosion have been observed in the river due to the results of the simulation. In the base scenario deposition of sediments mainly takes place in the lower reaches where the flow velocities are low to facilitate aggradation. On the other hand, erosion is localised in the higher parts particularly in those parts of the section with a steeper slope and an increase in the speed of flow. This is within the common sediment transport relationships characteristic of meandering river systems where deposition usually occurs on the inside bends and erosion occurs on the outside bends.

When the flow rate is elevated in a wet climate, the river increases the sediment carrying capacity, resulting in further erosion mainly on the external curves of meanders (Alsultani *et al.*, 2024). At the same time, there is an increase in the deposition of sediment in the floodplain and the lower reaches. On the other hand, dry climate scenario leads to a decrease in sediment transport capacity which leads to a decrease in the rate of erosion especially at the outer bends and hence increases the sediment deposition along riverbanks and floodplain.

These dynamic processes are measured as the volume of sediment deposition and erosion on an annual basis, as shown in Figure 6. Sediment deposition is the sum of all the annual volumes of sediment deposited on the floodplain and riverbanks and sediment erosion is the sum of all the annual volumes of sediment eroded off the riverbanks and main channel. The combination of these measures provides a complete evaluation of morphodynamic behaviour of the river in different hydrological and climatic conditions revealing a complex relationship between the supply of sediments, the transport capacity and the channel morphology.

SENSITIVITY OF MEANDER SHAPE TO CHANGES IN FLOW, SLOPE AND SEDIMENT

The model's sensitivity analysis reveals that river meander shape and dynamics are highly responsive to changes in flow, slope and sediment transport, as summarised in Figure 7. Among these variables, flow is the most dominant driver: increased flow velocity accelerates meander migration and enhances sinuosity, while reduced flow narrows the channel and slows migration. Slope also influences meander behaviour; steeper slopes increase erosion and sediment transport, promoting dynamic meanders, whereas flatter slopes result in more stable and slowly migrating channels.

Sediment supply significantly affects channel form. In the wet climate scenario (2085), the highest increases (+20% flow, +5% slope, +20% sediment) lead to pronounced aggradation, wider channels and increased sinuosity. In contrast, the upstream dam scenario (2040) (–10% flow, +2% slope, –15% sediment) results in channel narrowing and stabilisation due to reduced sediment and flow. The dry climate scenario (2055) (–15% flow, –3% slope, –10% sediment) further emphasises reduced migration and straightening of meanders. Meanwhile, the land use change

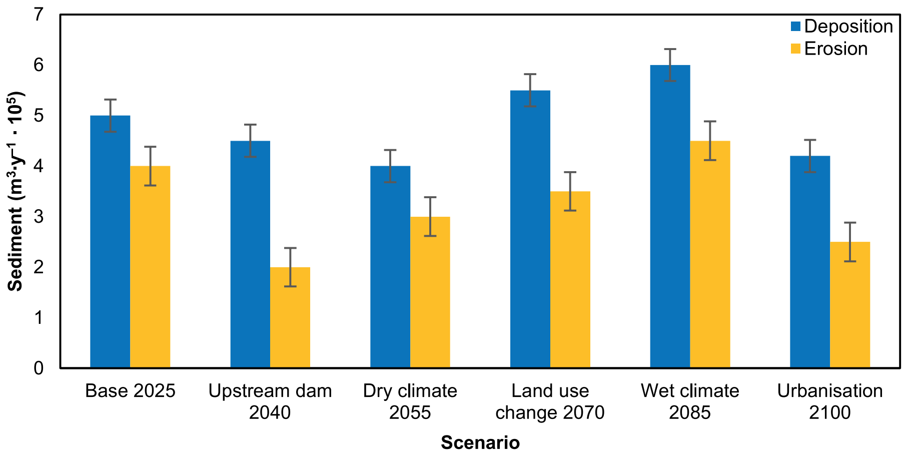

Fig. 6. Predicted sediment deposition and erosion trends; source: own study

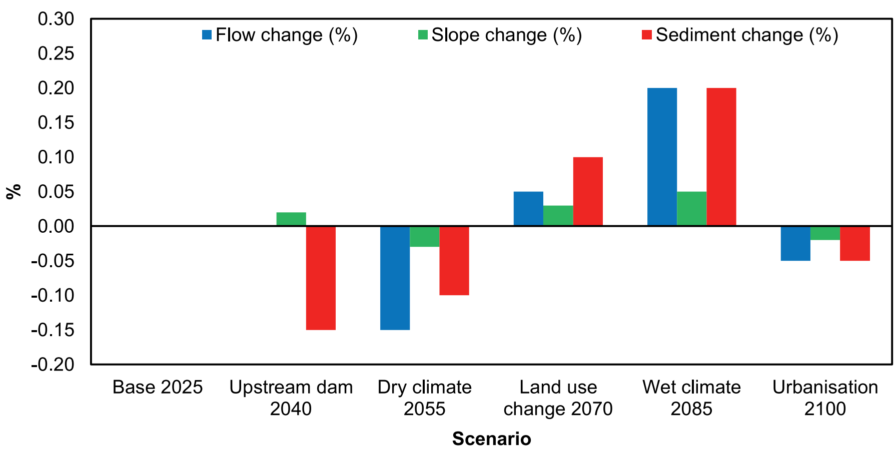

Fig. 7. Sensitivity analysis of meander shape to flow, slope and sediment; source: own study

scenario (2070) (+5% flow, +3% slope, +10% sediment) yields moderate increases in channel width and sinuosity. Finally, urbanisation (2100), with slight decreases across all variables (−5% flow, −2% slope, −5% sediment), shows minimal changes, leading to modest stabilisation.

Lastly, the findings distinctly demonstrate that flow changes are the most significant modifiers to meander evolution with slope and sediment changes being the secondary modifiers, which affect the magnitude and character of channel response.

SHATT AL-HILLA'S GEOMORPHOLOGY

The results of this work are useful in studying the geomorphology of the Shatt Al-Hilla River. The interaction of the velocity of flow, sediment transportation, and the bank composition is of great influence on the meandering nature of the river. The trends of meander migration and channel geometry are predicted to cause the river Shatt Al-Hilla to experience major morphological changes in the next several decades because of climate change and human actions. Such changes can be the changes in the course of the river, the pattern of the sediment deposition and the reduced or increased rate of erosion along the banks.

Meanders of the geomorphology of the Shatt Al-Hilla River are notable aspects of the river that affect the development of the floodplain and the movement of sediments. The predictions in the model show that the wet and dry climate scenarios will result in major changes in the morphology of the river, which may have consequences on the flood management and stability of the riverbanks. The scenario of a dry climate and also the upstream dam scenarios propose that channel incision is likely to increase the risk of floods in the regions that are already covered by natural meanders.

To better illustrate these dynamics, the predicted meander migration rates, bank erosion rates, sediment deposition change and flood risk index under different hydrological and anthropogenic scenarios are presented in Figure 8.

These results emphasise that wetter climate conditions enhance lateral migration and bank erosion, leading to wider channels, while drier conditions and upstream regulation restrict channel migration and promote incision. These opposite trends underscore the need to employ adaptive management measures to strike a balance between flood control, navigation and ecological sustainability in the Shatt Al-Hilla reach.

The estimated rates of meandering migration were different in the three modelled scenarios which showed that hydrodynamic and soil boundary conditions were very sensitive, as shown in Figure 9. During the low-flow state, the migration was rather moderate, 0.08–0.15 $m \cdot y^{-1}$, and the associated erosion rates along the outer banks were also low, 0.05–0.10 $m \cdot y^{-1}$. The changes in channel width during such condition were also weak with an average of 1.5–2.0 m which represents relatively held hydraulic behaviour.

Conversely, more significant changes were obtained in the medium-flow scenario. Migration was now reaching 0.22–0.35 $m \cdot y^{-1}$ with erosion rates of 0.15–0.25 $m \cdot y^{-1}$ on the outer banks. The channel also showed a significant widening effect with

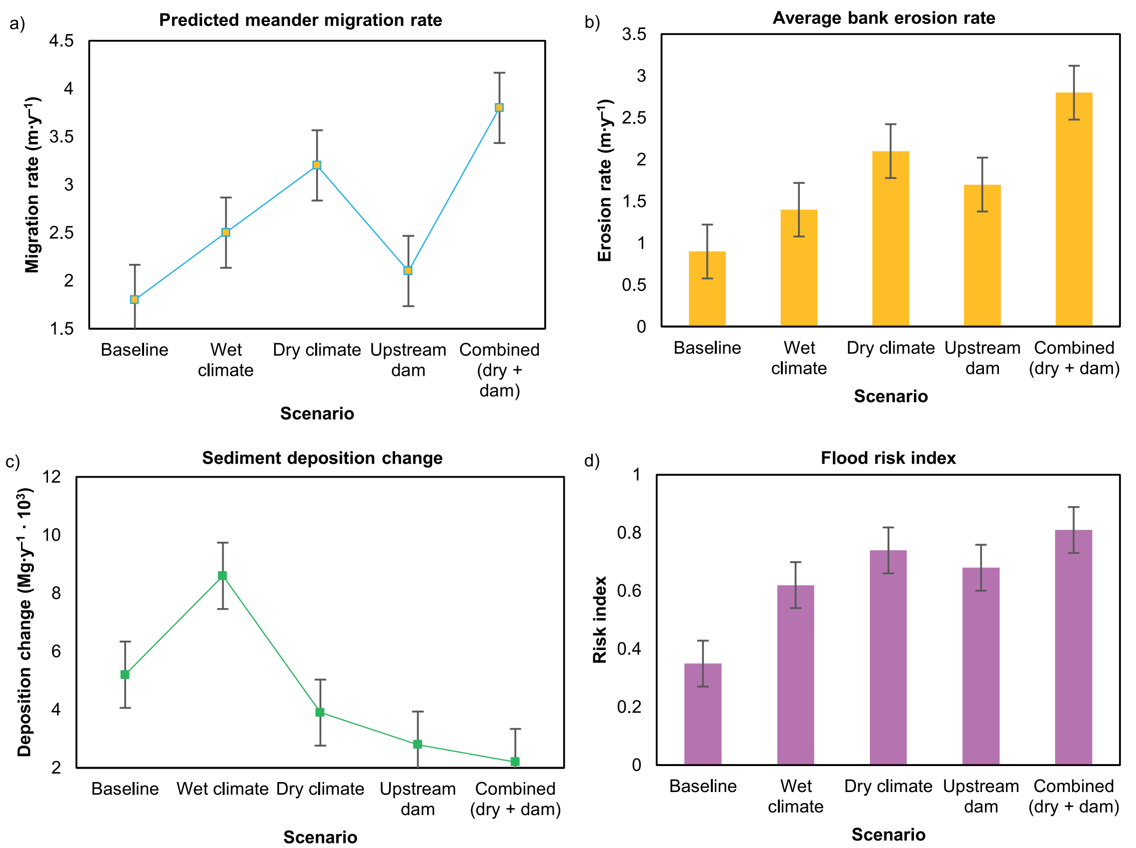

Fig. 8. Predicted morphological changes (under different scenarios): a) predicted meander mitigation rate, b) average bank erosion rate, c) sediment deposition, d) flood risk index; source: own study

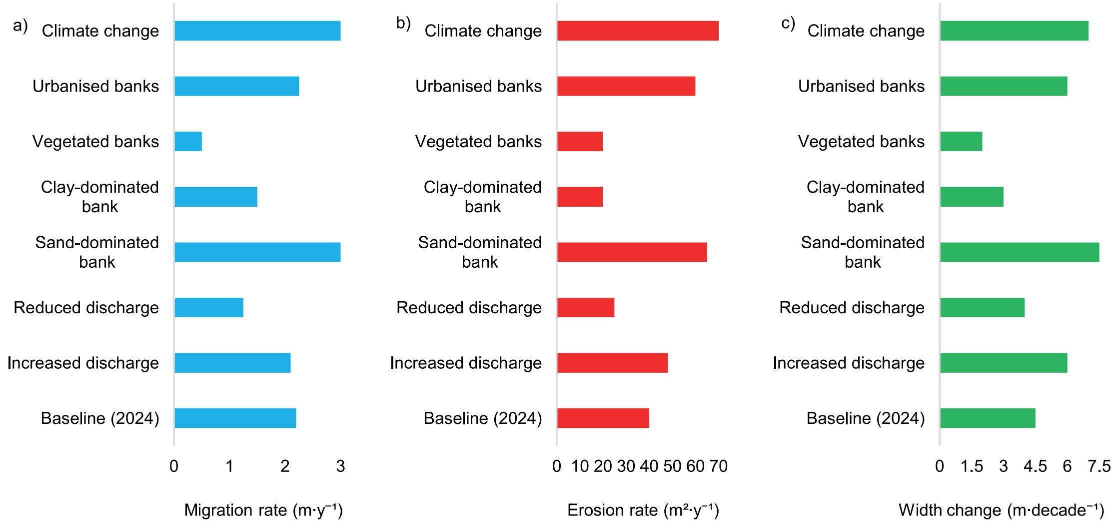

Fig. 9. Predicted parameters of investigated river under different flow scenarios: a) meander migration rates, b) erosion rates, c) channel width changes; source: own study

an increase of 3.0–4.5 m, which is more indicative of a more active morphogenesis to the increased energy flow.

The most critically high-flow condition took place, and the bank erosion rate increased to 0.30–0.50 $m \cdot y^{-1}$, and the migration rates reached 0.40–0.65 $m \cdot y^{-1}$. In this case, the widening of channels went to 6.0–8.5 m, which means a high degree of lateral instability. These values imply that extreme discharges can speed up meandering development and alter channel geometry drastically in rather short timeframes.

The situation-to-situation comparison shows the nonlinear increase in morphodynamic responses. As much as low flow conditions result in relatively stable reaches, the shift to medium and high flows shows a steep rise in erosion, migration and width expansion. The findings emphasise the importance of considering both hydrological variability and sediment-erosion processes in predictive models in the assessment of the future risks and restoration strategies of the Euphrates River in the Shatt Al-Hilla reach.

COMPARATIVE ANALYSIS

This study enhances the fluvial morphodynamics by introducing a new two-dimensional model, which involves hydrodynamics, sediment continuity and bank erosion mechanism to forecast the future change of meandering in the Shatt Al-Hilla River. In contrast to the earlier studies in the region that have mainly been dependent on empirical formulations or short-term field observations, the current framework explicitly integrates remotely sensed centreline information and process-based modelling over a 75-year forecast period. By having this long-term view, a more powerful evaluation of channel adjustment mechanisms across varying hydrological and anthropogenic stressors can be done.

The calculated meandering rates, as high as 0.65 $m \cdot y^{-1}$ in the case of high flows, are within the range of similar low-gradient alluvial rivers of the world (e.g., Zhao *et al.*, 2022; Mageed, Riyadh and Abbas, 2024). Nonetheless, the morphodynamic reaction of the Shatt Al-Hilla reach is unique because through interaction of upstream control and increased land-use transformation. As an example, the measured reduction of sinuosity in the conditions of the dam regulation is consistent with the stabilisation trends of channels observed by Hasan *et al.* (2024) and others, but our results also suggest that even stronger stabilisation effect may occur due to the urbanisation-induced reduction of the sediment and artificial strengthening of the banks. This implies that natural hydrologic variability in channel regulation can be overcome by anthropogenic interventions.

The use of a variety of the future scenarios, i.e. climate variability, dam regulation, deforestation and urbanisation, in a single morphodynamic modelling framework is also a significant contribution of this study. This type of all-encompassing scenario-based study has not been tried in Iraqi river systems, and the majority of earlier studies have concentrated on short term sediment transport evaluations or localised hydraulic modelling. Numerous drivers have been incorporated and therefore enable a more realistic study of the effect of the compounds, and this shows how low-gradient rivers are vulnerable both to the changes in climate and also to the swift man-made changes at the catchment size.

The sensitivity analysis highlights the overwhelming influence of flow in controlling meander evolution, which supports the results of previous experimental and numerical research (e.g., Das *et al.*, 2025). Meanwhile, this paper offers new data that the slope and sediment supply differences, which are secondary, have critical controls on channel adjustments in extent and direction. The perspective of layered sensitivity provides an improvement to the conceptual models by illustrating that minor adjustments in slope or sediment inputs can significantly enhance or reduce the morphodynamic responses to flow.

Climatic, dam regulation and land-use scenario modelled outcomes, though in line with anticipated hydrodynamic behaviour, give more insight when interpreted in a low-gradient alluvial system. This amplified meandering movement in wet conditions is due to the amplified stream power and bank shear stresses which increase the erosion and the movement of the sediments laterally. On the contrary, dry climatic conditions and upstream dam settings result in decreased sediment input and lower flow competency, which facilitates channel incision and armouring a trend also recorded in the Tigris-Euphrates basin and other semi-arid rivers, like the Nile Delta (Lin *et al.*, 2022; Liu *et al.*, 2025).

The response of the Shatt Al-Hilla River is a geomorphic sensitivity characteristic of low slope, fine-grained systems in which a relatively small hydrologic disturbance can cause significant planform changes. This type of feedback has been observed in the literature of the Mississippi, Yangtze and Murray-Darling rivers (Hu *et al*., 2023; Zheng *et al*., 2024). Therefore, the directional consequences of the scenarios are quite intuitive, but the scale and spatial variability of the anticipated morphodynamic variations indicate the increased sensitivity of arid lowland rivers to compounded climatic and anthropogenic strains. It is in this respect that adaptive management strategies should be incorporated that incorporate hydrological variability, sediment continuity and local geomorphic context in determining future stability of regulated river systems.

Practically, the results highlight the need to adopt adaptive management plans to take into consideration hydrological variability, sediment regime and bank material properties to reduce the future risk of channel instability, bank retreat and flooding. The future trends of higher levels of lateral migrations and oxbows during 2100 require the active management of sediments and permanent observation to maintain the ecological and hydraulic integrity of the Shatt Al-Hilla River system.

Overall, the comparative analysis highlights the twofold novelty of the study: (i) methodological, as it combines remote sensing with process based morphodynamic modelling to examine the evolution of the river over a long period of time in a data sparse setting, (ii) substantive, in the sense that it will reveal a unique path of the Shatt Al-Hilla River when acted upon by opposing climatic and anthropogenic factors. The findings are valuable not just to the local knowledge of the morphodynamics of the Euphrates River, but also to the hydro-geomorphology as a whole, as the conclusions provide a dependable decision-support instrument on managing the river and infrastructure planning and climate adaption policies in other low-gradient systems.

CONCLUSIONS

This paper has described how a two-dimensional mathematical model was developed and used to model the long-term process of interaction of hydrodynamics, sediment transport and river meandering in the Shatt Al-Hilla River, central Iraq. This model used the Saint-Venant shallow water equations together with the Exner sediment continuity equation and a bank erosion model which was developed using the excess shear stress approach. It showed a good performance after calibration and validation (Nash–Sutcliffe efficiency (NSE) = 0.82, coefficient of determination (R^2) =0.89, root mean square error ($RMSE$) = 5.4 m). The specific conclusion may be summarised as follows.

1. Simulation of long-term scenarios up to 2100 showed extensive movement of channels, alteration of sinuosity and displaced erosion-deposition patterns that occurred due to variability of climate and human activities.
2. The Shatt Al-Hilla River has very high morphological sensitivity to hydrologic changes, sediment load and land use alterations. As the simulation period of 2025–2100 approached, the channel containing the compound meander changed to a very dynamic and possibly unstable system, as the meander migration rates differed between upstream dam conditions (0.65 $m \cdot y^{-1}$) and wet climatic conditions with more than 2.5 $m \cdot y^{-1}$.
3. The most important parameter that regulated meander evolution was flow velocity. Flow rises, 0.5 $m \cdot s^{-1}$ (shallow water) to 2.5 $m \cdot s^{-1}$ (deep water), which hastens meandering migration and sinuosity. In the wet climate conditions (2085), the flow was raised by about 20% stipulating a significant growth in the meander wavelength and channel width up to 15%.
4. The channel morphology was affected significantly by changes in the supply of sediments. The interventions that reduced the sinuosity and narrowed the channel by approximately 10% as a result of 15% of sediment removal by upstream dam regulation (2040). On the other hand, the land use change situations (deforestation in 2070) raised the amount of sediment input by 10 and opened the channels by 12% and increased the rates of lateral migration. The channel slope variations (from −3 to +3) also modulated the rate of erosion and sediment transport, which affected the meander dynamics.
5. The morphology of the Shatt Al-Hilla River changes very much across conditions: wet weather broadens the channels, sinuosity and meander migration (up to 2.5 $m \cdot y^{-1}$); dry weather and the presence of dams narrows the channel, stabilises and slows down the migration (0.8–1.2 $m \cdot y^{-1}$); deforestation enriches the channel and migration, making it wider; urbanisation makes flow and movement a bit less active, making the channel more uniform and gradual.
6. Sediment connectivity and natural variability of flow is an important aspect to maintain morphodynamic diversity and river stability. Management interventions should account for the strong influence of flow and sediment supply to mitigate risks of channel incision, bank erosion and flooding, especially under future climate and land use scenarios.
7. The model forecasts significant morphological transformations over the next century, with some scenarios predicting channel instability and oxbow formation by 2100.

The developed modelling framework offers a transferable tool for other Euphrates tributaries and similar alluvial rivers across the Middle East and North Africa, where long-term morphodynamic predictions are constrained by limited data. Its integration of satellite-based monitoring and physically-based process representation makes it valuable for river management, flood risk assessment and climate adaptation planning.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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