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Calibration of a telemac-2d hydrodynamic model for the port of San Pedro (southwestern Côte d'ivoire)

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Abstract

This study presents the calibration of a two-dimensional TELEMAC numerical model applied to the San Pedro port area, a strategic location on the Southwestern Ivorian coastline and the world's leading cocoa export hub. The novelty of this work lies, first, in the inaugural application of the TELEMAC system to the San Pedro harbor, and second, in the establishment of reference calibration coefficients enabling the use of tidal forcing derived from the global TPXO model for the Ivorian coast. The TELEMAC-2D-TPXO configuration further integrates key coastal morphological features such as the Tombolo, groins, and headlands, thereby enhancing the refinement of simulations and providing a more accurate representation of local hydrodynamics. Calibration results identified optimal tidal range and sea-level adjustment coefficients of 1.04, yielding a root mean square error (RMSE) of 0.05. This TELEMAC model thus offers a robust foundation for hydrodynamic analysis and supports the planning of potential port expansions.

Keywords: Hydrodynamic Calibration; Port of San Pedro; TELEMAC-2D; TPXO Model; Coastal Morphology; Water Levels

1. Introduction

Due to its intensive and continuously expanding maritime activity, the Port of San Pedro is facing considerable environmental and operational challenges that require optimal resource management. A thorough understanding of the dynamics of this area is therefore essential. For this purpose, a two-dimensional TELEMAC numerical model was developed. Before being applied to simulate the hydrodynamic functioning of the San Pedro port area, the model underwent calibration. The present work determines the optimal parameters that enable the model to best represent the real conditions in this zone.

1.1. Study Area

The study area (Fig. 1) is located in the city of San Pedro, within the Bas-Cassandra region of Côte d'Ivoire, in the Gulf of Guinea. This area extends approximately 7 km in length and about 1 km on average from the shoreline to the offshore boundary. The northernmost limit of the model is about 2.5 km offshore, opposite the port.

The central element of this study area is the Autonomous Port of San Pedro, a deep-water port with an access channel 2.5 km long and 200 m wide, a western breakwater 300 m long, and an eastern breakwater 400 m long. The port infrastructure also includes 4.2 km of quays, water depths reaching up to 16 m, and a total surface area of 2,500 hectares (25 km^2).

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The shoreline included in the model covers all beaches and infrastructures, extending from the tombolo in the west to the river zone in the east, located 1.35 km downstream of the river mouth.

Figure 1 Area covered by the model represented by the white line on the coast and at sea

- Source map of Africa: https://commons.wikimedia.org/w/index.php?curid=88681660
- Source map of Ivory Coast: https://commons.wikimedia.org/w/index.php?curid=65038670

2. Materials and Methods

2.1. Mesh

A triangular unstructured mesh was used (equilateral in homogeneous zones and isosceles in transition areas). The mesh consists of 1267 nodes and 2250 elements, with cell sizes of 250 m offshore and 50 m near the coast (Fig. 2).

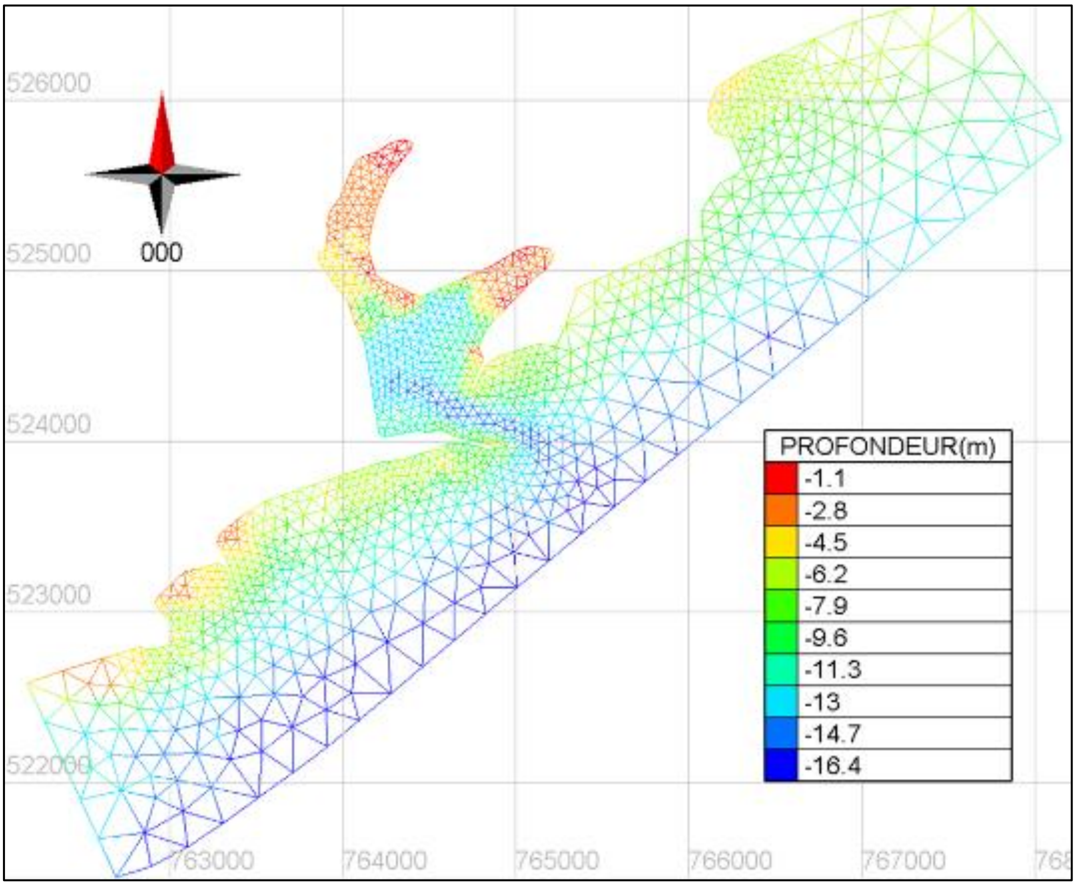

Figure 2 Interpolated mesh based on the bathymetry of the study area

2.2. Bathymetry

A multi-source bathymetry was used. It mainly consists of digitized bathymetric charts (processed with QGIS) from the hydrographic service of the Port of San Pedro. The bathymetry of the harbor and the northern and eastern branches (2016) was combined with that of the underwater beach in front of the port (2008). To extend coverage offshore, additional bathymetric data of the continental shelf (Monde, 1997) were included. The resulting bathymetry was interpolated onto the model grid (Fig.2).

2.3. Boundary Conditions

At the upstream boundary, river discharges were derived from the reanalysis of Morell & Toilliez (1975). At the downstream boundary, water levels were taken from the TPXO tidal prediction model. Wave characteristics were extracted from Yao et al. (2018). Wind data at 10 m above ground level were obtained from the NASA POWER database (NASA, 2024).

2.4. Governing Equations and Model Evaluation

The TELEMAC-2D model of the Petaluma suite solves the depth-averaged shallow water equations (Saint-Venant equations), which are derived from the three-dimensional Navier–Stokes equations under the shallow water and hydrostatic pressure assumptions. In this study, TELEMAC-2D was adopted, assuming negligible vertical variations and constant density.

The governing equations consist of the continuity equation (Equation (1)) and the momentum equations in the x and y directions (Equations (2)– (3)).

2.5. Continuity equation

$$\partial U/\partial x + \partial V/\partial y = 0 \quad (1)$$

Momentum equation in the x-direction

$$\partial U/\partial t + U\,\partial U/\partial x + V\,\partial U/\partial y = -\partial P/\partial x + \mu\,(\partial^2 U/\partial x^2 + \partial^2 U/\partial y^2) + FX \quad (2)$$

Momentum equation in the y-direction

$$\partial V/\partial t + U\,\partial V/\partial x + V\,\partial V/\partial y = -\partial P/\partial y + \mu\,(\partial^2 V/\partial x^2 + \partial^2 V/\partial y^2) + Fy \quad (3)$$

where U, V (m/s) are the depth-averaged velocity components; P (Pa) is the pressure; g (m/s^2) the gravitational acceleration; μ (m^2/s) the kinematic viscosity; t (s) the time; x, y (m) the horizontal spatial coordinates; and FX, Fy (m/s^2) the external source terms (e.g., wind stress, Coriolis force, bed friction).

The accuracy of the numerical model was assessed using two statistical indicators (Equations (4)– (5).

Root Mean Square Error (RMSE)

$$RMSE = \sqrt{(1/n)\,\Sigma\,(HC - ho)^2} \quad (4)$$

where n is the number of samples, HC the computed water level, and ho the observed water level.

Table 1 Model quality assessment according to RMSE values

Qualification	RMSE
Excellent	< 0.2
Good	[0.2; 0.4[
Average	[0.4; 0.7[
Poor	[0.7; 1]
Bad	> 1

Correlation coefficient (R)

$$R = Cov\,(HC, HO)\,/\,(\Sigma HC \cdot \Sigma HO) \quad (5)$$

where HC and ho are the computed and observed values, ΣHC and ΣHO their standard deviations, and Cov (HC, ho) their covariance.

2.6. Calibration and Validation Data

Calibration was performed using water level data recorded at tide gauge No. 1 (Fig. 3, M1, 4°44'16.50"N / 6°36'53.87"W) for the period of August 8 2020. These measurements covered 72 hours, with water heights ranging from approximately 0.5 m to 1.5 m (Fig. 4).

Validation was conducted with an independent dataset from the same tide gauge for a 24-hour period on 1 August 2002.

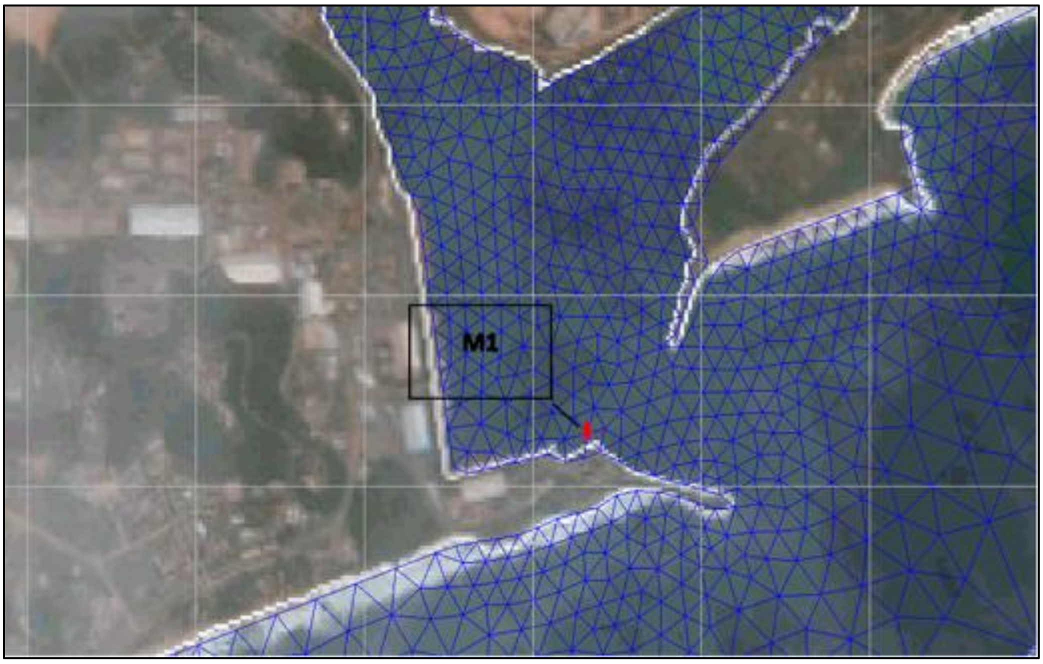

Figure 3 Location of the calibration point, the M1 tide gauge

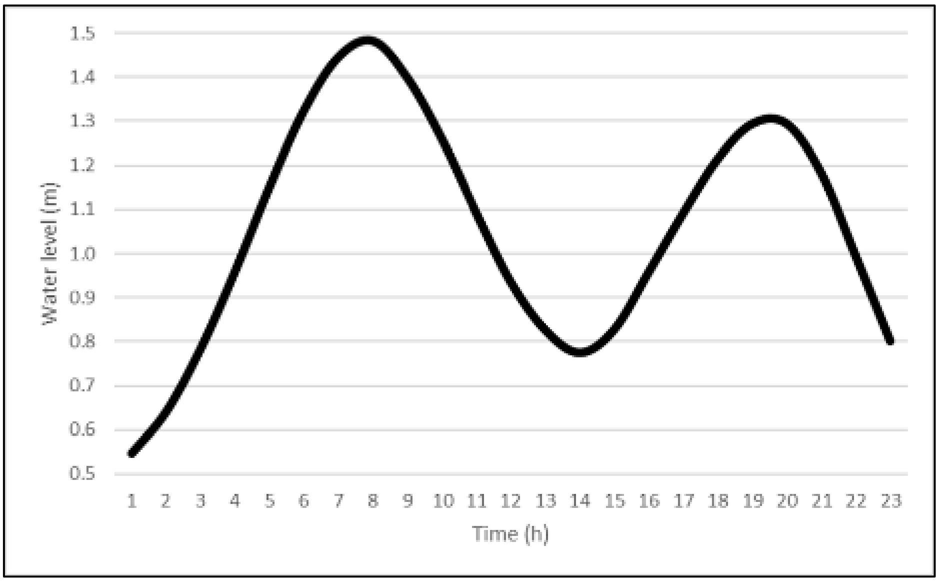

Figure 4 Water levels measured at tide gauge 1 foot August 8, 2020

3. Results and Discussion

3.1. Calibration of Water Levels

The calibration, based on time series of observed water levels, demonstrated very good agreement between measurements and model outputs. The comparison (Table II) yielded a Root Mean Square Error (RMSE) of 0.0514, which, according to the evaluation criteria, qualifies as excellent.

Table 2 Test values for the different tuning coefficients for the TPXO model

Curve name	Parameters	Correlation	RMSE
SLTR1	TR=SL=1	0.989348	0.0643
SLTR1.02	TR= SL=1.02	0.98934739	0.0544
SLTR1.03	TR=SL=1.03	0.989349247	0.0519
SLTR1.*04*	*TR=SL=1.04*	*0.989357*	*0.0514*
SLTR1.05	TR=SL=1.05	0.98936	0.0529

Furthermore, the calibration coefficient of the tidal range and that of the sea level derived from the TPXO model for the study area were both established at 1.04. These results indicate that the TELEMAC configuration, once calibrated, successfully (Fig. 5) reproduces the observed tidal dynamics within the port area of San Pedro.

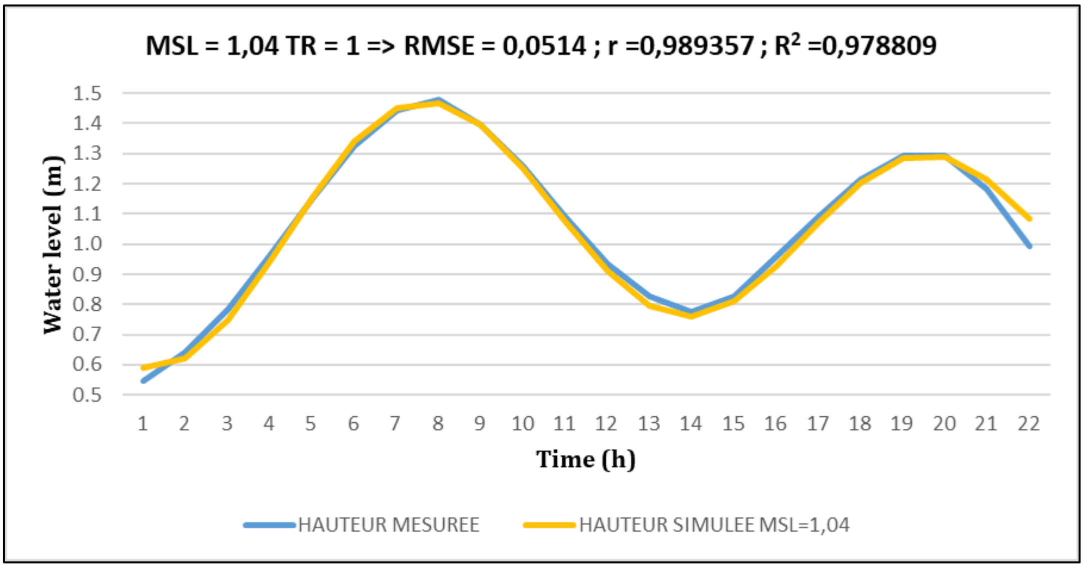

Figure 5 TPXO calibration of water levels: the measured height (blue) is compared to the simulation curve (red) giving the best results

3.2. Validation

Validation was carried out using an independent 24-hour dataset of water levels measured at tide gauge No. 1 on 1 August 2002. The comparison between observations and simulations (Fig. 7) showed that the model reproduced the temporal variability of water levels with high fidelity.

The comparison between observed and simulated values yielded a correlation coefficient greater than 0.98, confirming the strong consistency between field data and numerical simulations. This result demonstrates the robustness of the calibrated TELEMAC-2D model in reproducing hydrodynamic processes in the port environment.

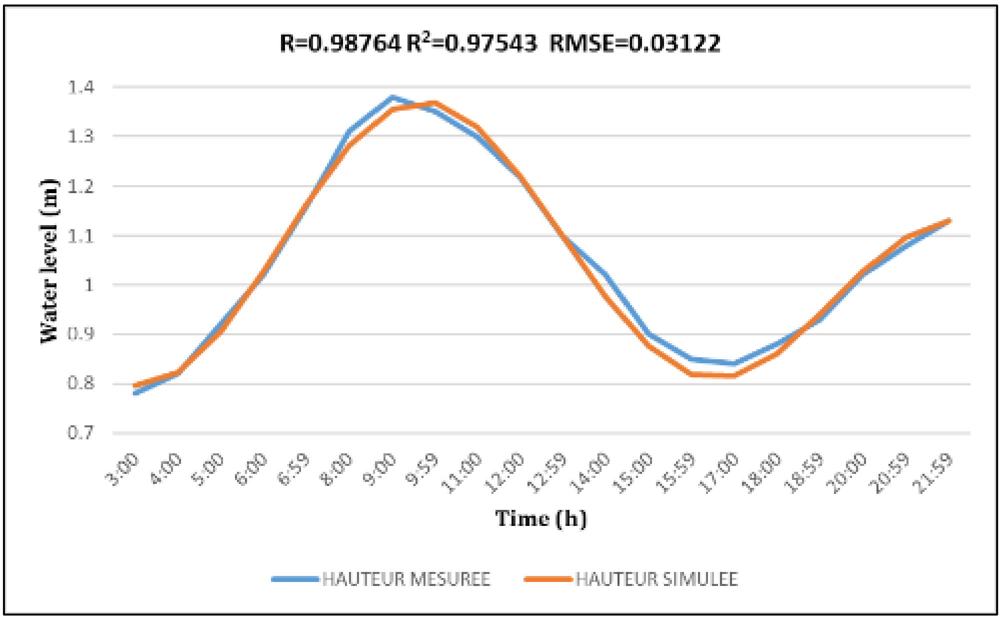

Figure 6 Validation by water levels measured on August 1, 2002, the measured height (blue) is compared to the simulation curve (red) giving the best results

3.3. Interpretation

The results of both calibration and validation highlight the ability of the TELEMAC-2D model to reproduce local hydrodynamics with a high level of accuracy. By incorporating regional tidal forcing from TPXO and detailed bathymetric data, the model captures the main tidal oscillations as well as the mean sea level variability in the study area.

Such performance confirms that the calibrated model provides a reliable basis for further applications, including scenario testing and support for port management and future development projects.

4. Conclusion

The calibrated model achieved a correlation coefficient of 98.9% with an RMSE of 5.14%, indicating excellent agreement with observations. Validation for an 18-year deviation from calibration yielded a correlation of 98.86% and an RMSE of 3.13%. The results obtained, characterized by a very good agreement between measurements and simulations, now constitute a reference for future regional tidal dynamics studies and for any use of the TPXO model in Côte d'Ivoire.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

Author Contributions

Conceptualization: Josias B. Nong be; Methodology: Ted-Edgar W. Yassi; Data curation: Ted-Edgar W. Yassi; Writing – original draft: Josias B. Nong be; Writing – review & editing: Josias B. Nong be, N'Guessan E. Yao,; Supervision: Ted-Edgar W. Yassi.

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Data Availability Statement

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

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT (OpenAI) for language refinement and formatting according to the Ocean Engineering guidelines. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the final version.

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