Technical Note: Operational calibration and performance improvement for a 1D hydrodynamic model in a data-scarce coastal area

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Abstract.

In this study, we address the challenges posed by data scarcity in hydrodynamic modeling within one of the most vulnerable coastal zones in the world—the Saigon-Dongnai tidal river system in South Vietnam. We investigate calibration strategies for a 1D hydrodynamic model using minimal in-situ data obtained from an existing local monitoring program, which provides 48 hours of measurements per month. Calibration using both directly measured water levels and discharge data derived from vertical velocity profiles yields the most accurate discharge estimates, with relative root mean square errors (rRMSE) ranging from -75% to -78% in the Saigon River and 23% to 29% in the Dongnai River, depending on tidal asymmetry. To further improve discharge estimation from the 1D model, we explore the coupling of a modified Manning-Strickler (MS) equation. Calibration results reveal distinct spatial variations in friction coefficients along the river system, highlighting the importance of localized adjustments. Incorporating this calibration technique significantly enhances model performance, reducing discharge rRMSE by 27% to 44% in the Saigon River and 11% to 29% in the Dongnai River, depending on tidal asymmetry. The study underscores the complexities of calibrating hydrodynamic models in data-scarce regions, with recommendations for future modeling endeavors including incorporating more accurate upstream boundary conditions. The long time-series of estimated water level and discharge provided by this study have practical implications for water resource management and decision-making in data-scarce estuarine systems and are provided in open-access for operational use.

1 Introduction

Tidal rivers represent intricate systems bridging continental surfaces and the ocean, where water levels and river discharge are profoundly affected by tidal movements. Consequently, the interplay between flooding and tidal constraints on water levels becomes pivotal, particularly in the context of flood protection, pollution management, and climate change adaptation characteristic of these areas. The complex back-and-forth advection coupled with dispersion makes it challenging to predict the propagation of sediment particles or pollutants in such environments.

The Saigon and Dongnai rivers in Vietnam serve as a notable case of a tidal river system, characterized by its flat watershed and, for the Saigon branch, the marginal significance of its net flow compared to tidal influence (Camenen et al., 2021). This river system flows through Ho Chi Minh City (HCMC), one of the most vulnerable megacities globally concerning climate change impacts (Lossouarn et al., 2016). Research has shown the critical need to understand its hydrodynamics for assessing flood risks (Vachaud et al., 2019), managing saline intrusion (Ngo et al., 2015; Nguyen et al., 2018), and mitigating pollution (Babut et al., 2019; van Emmerik et al., 2019) and eutrophication (Nguyen et al., 2022).

The limited availability of data for evaluating flow and tidal variations in this region negatively impacts the management of these rivers and their source reservoirs. In April 2024, an intense drought swept through southern Vietnam, with temperatures soaring to nearly 40 degrees Celsius, as reported by several news outlets (Orie, 2024; FranceInfo, 2024). This heatwave significantly impacted irrigation activities and fish populations in the Dongnai region, exemplifying the vulnerability of human activities to climate change in such areas. Furthermore, it underscores the importance of modeling efforts for this hydrosystem and the necessity of providing free and open-access time-series data of hydraulic variables. Therefore, numerical modeling emerges as a strategic tool for elucidating the behavior of such complex tidal river systems.

The current body of literature contains a few examples of hydrological and hydraulic modeling efforts in the region. For instance, Camenen et al. (2021) estimated the discharge of the Saigon River using two water level measurement points and a modified Manning-Strickler equation. However, their methodology allows discharge estimation at only one point in the river corresponding to the location of river discharge measurements. As a result, their approach is limited to one specific location in the Saigon branch. In contrast, our study employs a 1D model that captures the full spatial extent of the Saigon-Dongnai river system, providing a more comprehensive representation of its hydrodynamics. Similarly, Khoi et al. (2022) employed the SWAT model to study the impact of climate change on the Saigon River's discharge. Their model calibration and validation relied on daily discharge data from 1981 to 2000 at four points along the river. Since the study focused on climate impact, the calibration was not as precise as it could have been; the primary requirement was a reference discharge to compare against future discharge estimates, thereby assessing the impact of climate change. This highlights the scarcity of recent, accurate, high temporal resolution discharge data for this system. This is partly due to the fact that traditional river discharge monitoring methods are labor-intensive, require minimum water depths, or necessitate prolonged measurement periods, making them costly and time-consuming (Eltner et al., 2020). Indeed, river discharge measurements have significantly declined over the past 30 years even in developed countries (Zakharova et al., 2020).

In complex, tide-dominated river networks, selecting an appropriate modeling approach depends on the primary objective and data availability. While 2D models are often preferred for floodplain inundation and urban flood mapping, they require high-resolution topography, detailed bathymetric data, and extensive calibration datasets, which are often unavailable in poorly gauged river systems. In contrast, 1D hydrodynamic models remain a computationally efficient and practical alternative when the main goal is to estimate discharge and water levels within the channel network. In many cases, flow remains largely confined to the riverbed, and a well-calibrated 1D model can provide accurate results with significantly lower computational demands. However, we acknowledge that when overbank flow, floodplain interactions, or urban drainage processes become dominant, a coupled 1D-2D or full 2D approach may be more appropriate. Our study provides a clear example of when a 1D model is sufficient and how targeted calibration can compensate for data limitations, making it a valuable tool for tide-influenced, data-scarce regions.

Hydraulic data availability varies significantly among rivers, even in regions with relatively good data coverage, and is particularly scarce in tropical areas (Wood et al., 2023; Scheiber et al., 2023). These limitations can be partially mitigated by using model-generated data (Xu et al., 2022; Heinrich et al., 2023). However, model calibration and validation require in-situ data, which is often lacking. The primary obstacle to modeling efforts for the Ho Chi Minh City region is the very limited amount of data for calibration and validation. Despite this, Scheiber et al. (2023) managed to set up an urban flood model for HCMC using only open-access satellite data and monthly mean river discharge from reservoir operations. Nonetheless, the model introduced significant uncertainties and limitations inherent to satellite data, aiming to provide preliminary flood maps rather than deterministic conclusions.

This paper aims to i. develop and validate a calibration methodology for improving 1D hydrodynamic modeling with minimal in-situ data by coupling a simple flow law and ii. to illustrate the utility of a low-cost modeling effort in understanding flow dynamics in a poorly gauged tidal river network. Leveraging a 1D hydrodynamic model developed at INRAE Lyon, previously validated on other tidal river systems like the Adour river (Camenen et al., 2022) or the Lower-Seine river (Mendez Rios et al., 2023), the study explores three calibration strategies for the Saigon-Dongnai river system using scarce in-situ measurements sourced from an already existing local measurement protocol. The calibration approaches put forward are: i. using direct measurements of water level, ii. using discharge data computed from vertical velocity profiles using the velocity index method and iii. using both sources of data. Calibration efforts focused on optimizing the Strickler coefficient, K_s, by minimizing a loss function comprising water level and discharge relative root mean square errors (rRMSE). Validation against independent measurements was then performed. Finally, a modified Manning-Strickler (MS) law was coupled with the hydrodynamic model to improve discharge estimation.

2 Materials and Methods

In this study, we employ two calibration approaches to achieve the most reliable estimations of water levels and discharge within the framework of a tidal river system within a data-scarce region.

First, we evaluate three distinct calibration strategies for a one-dimensional (1D) hydrodynamic model, each using a different combination of calibration data, as detailed in Section 2.4. The performance of each strategy is assessed by validating model outputs against independent datasets from non-overlapping time periods.

Second, to address data limitations and enhance discharge estimation, we integrate a modified Manning-Strickler (MS) law with the 1D model. This coupling is achieved by using the energy slope computed by the model as input to the MS law. The MS law undergoes a secondary calibration phase using the same discharge data as the 1D model, after which the discharge outputs are validated against an independent dataset from non-overlapping periods.

2.1 Case study: the Saigon-Dongnai river system

The Saigon-Dongnai river system, situated in South Vietnam (Figure 1), comprises two main rivers: the River Dongnai and the River Saigon. The River Dongnai originates from Central Vietnam and flows southward through the Tri An reservoir, while the River Saigon originates in Southeastern Cambodia and flows through to the Dau Tieng Reservoir. Downstream of the Dau Tieng reservoir, the River Saigon traverses a highly urbanized area, Ho Chi Minh City (HCMC), which has significant impacts on water quality due to inadequate wastewater treatment (Nguyen et al., 2019). The region features predominantly flat terrain, and the river system is heavily influenced by tides (Camenen et al., 2021).

The instantaneous flow in the Saigon-Dongnai river system can fluctuate between -2000 m^3/s to +2500 m^3/s, with the net discharge typically remaining below 100 m^3/s and occasionally reaching up to 300 m^3/s during peak flow seasons. The River Saigon, crossing through HCMC, is interlinked with numerous urban canals and serves as a tributary to the River Dongnai. In contrast, the Dongnai river exhibits substantially higher net discharge values, typically an order of magnitude greater, with monthly averages ranging from 200 m^3/s during the dry season to 1200 m^3/s during the rainy season (see Figure 4).

2.2 1D Hydrodynamic modelling: MAGE

We employ the MAGE (MAillé GÉnéralisé) code that solves the Saint-Venant equations (Souhar and Faure, 2009), comprising the mass conservation equation (Eq. 1) and momentum conservation equation (Eq. 2). These governing equations are derived from the Navier-Stokes equations for mass and momentum conservation, under the assumptions of an incompressible fluid, hydrostatic pressure distribution, and small channel bottom slopes. These equations are typically expressed in terms of wetted area, which depends on water level and discharge as the primary variables. Consequently, the mass and momentum conservation equations can be formulated as follows:

$$\frac{\partial A_w}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat}, \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\beta \cdot \frac{Q^2}{A_w}\right) + g \cdot A_w \cdot \frac{\partial Z}{\partial x} = -g\frac{Q \cdot |Q|}{K_s^2 \cdot A_w \cdot R_h^{4/3}} - g \cdot A_w \cdot J_s + k \cdot q_{lat} \cdot \frac{Q}{A_w}, \tag{2}$$

where A_w represents the wet section, Q the water discharge, q_{lat} a lateral input or output (overflow), Z the water surface elevation, K_s the Strickler coefficient, R_h the hydraulic radius and J_s the a singular head loss. k is a boolean variable such that $k = 1$ if $q_{lat} < 0$, and $k = 0$ otherwise.

Friction head losses are modeled using the classical Manning-Strickler law. MAGE employs a finite difference method utilizing a Preissman scheme and an iterative approach (Newton-Raphson) for solving the system of non-linear discrete equations (Equations 1 and 2).

The model for the Saigon-Dongnai river system was constructed utilizing the MAGE code via the PamHyr interface presently written in Java and soon to be accessible as a Python interface (Rouby et al., 2024; Camenen et al., 2023). This interface offers capabilities for editing network topology, geometry (including cross-sections and mesh), hydraulic conditions (such as friction coefficients and boundary conditions), setting numerical parameters, and visualizing primary results.

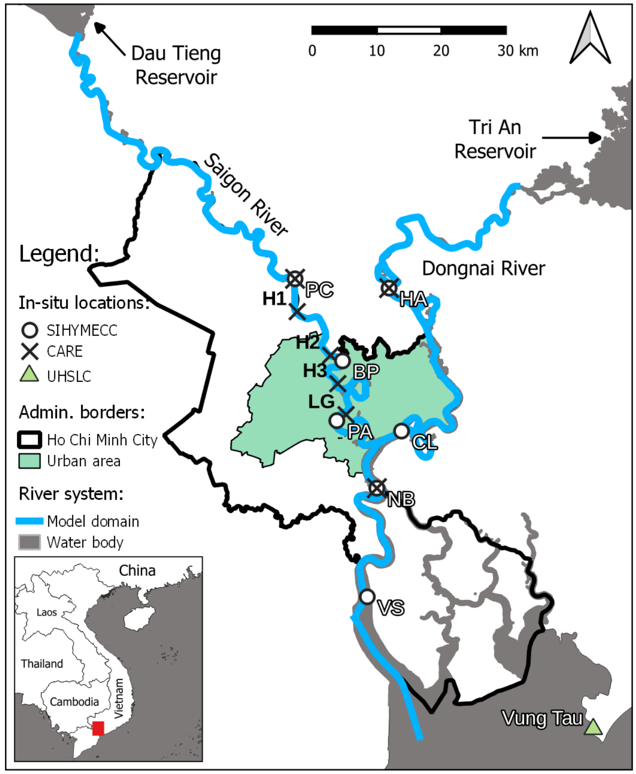

Figure 1. Map of the study area. The estuary water bodies (grey) and the MAGE model domain (blue) with the Dongnai river (right) and its Saigon river branch (left) can be seen. Locations of river measurements from the Sub-Institute of Hydrometeorology and Climate Change (SYHIMECC, white dots) and from the Center of Asian Research on Water (CARE, black crosses) are also shown. The Saigon river presents six measurement locations namely, Phu Cuong (PC), Hobo 1 (H1), Hobo 2 (H2), Binh Phuoc (BP), Hobo 3 (H3), La Garden (LG) and Phu An (PA). The Dongnai river presents four measurement locations namely, Hoa An (HA), Cat Lai (CL), Nha Be (NB) and Vam Sat (VS). The Vung Tau tidal gauge from the University of Hawaii Sea Level Center (UHSLC) is depicted as a green triangle. The Ho Chi Minh City area and the heavily populated urban center are depicted by a black line and a green polygon, respectively. The area shown in the larger map is represented by the red box in the overview map.

The river system was built using 83 cross-sections along the Saigon river and 36 cross-sections along the Dongnai river (Camenen et al., 2023). The bathymetry data was extracted from bathymetry surveys conducted by the SYHIMECC in 2016 (Nguyen et al., 2021). The primary challenge encountered in this modeling work is the lack of direct measurements of water inputs, not only from the dams but also from tributaries and irrigation canals, which are numerous and significantly influenced by tidal dynamics. These characteristics were left out of the modelling effort.

Given the geometry of our system domain (Figure 1), the MAGE model requires three boundary conditions: (i) a discharge time series at the source of the Saigon River branch, namely, the Dau Tieng reservoir; (ii) a discharge time series at the source of the Dongnai River branch namely, the Tri An reservoir; and (iii) a water level time series at the river mouth. A significant challenge in modeling arises from the lack of data for the upstream boundary conditions, as tidal influence extends to both upstream dams. As an initial approximation, we will use mean monthly discharge from the period of 2012-2016 as reported by Nguyen et al. (2019). The upstream boundary conditions are presented in Figure A1 in the Appendix A. Additionally, a sensitivity analysis showed that the uncertainties on these upstream boundary conditions have a negligible impact on the instantaneous flow dynamics in the river system (Camenen et al., 2023). However, if the instantaneous discharge were to be filtered to obtain the net discharge, we would retrieve the upstream boundary condition. Hence, the model output cannot be used to access the net discharge of these rivers as this variable is an input to the model.

For the downstream boundary condition, we use data from the Vung Tau tide gauge obtained from the research-quality dataset available through the Joint Archive for Sea Level of the University of Hawaii Sea Level Center (UHSLC) (Caldwell et al., 2015).

2.3 Manning-Strickler law for operational applications

The MAGE model has difficulty in accurately predicting both water level and river discharge in the Saigon branch (Camenen et al., 2023) especially within the framework of data scarcity. Hence, we opted to couple this model with a modified Manning-Strickler (MS) law that has demonstrated efficacy for different tidal rivers (Camenen et al., 2017), including for the Saigon River branch (Camenen et al., 2021; Rodrigues do Amaral et al., 2024). Illustrated in Figure 2, the energy slope output from MAGE feeds into the modified MS law. This law is formulated as follows:

$$Q(t) = \text{sign}(S) \cdot K_s \cdot A_w \cdot R_h^{2/3} \cdot \sqrt{|S(t)|}, \tag{3}$$

with Q representing the water discharge [m^{3}s^{-1}], K_s the Manning-Strickler coefficient [m$^{1/3}$s^{-1}], $R_h = A_w/P_w$ the hydraulic radius [m], where A_w denotes the wet section [m^2] and P_w the wet perimeter [m]. The term sign(S) equates to the sign of the slope, S, taking on values of +1 or -1.

The energy slope, S [-], is assumed to be equal to the water slope and is derived from the water surface elevation output by MAGE around the point where discharge estimation from the MS law is desired. This equation can only yield a discharge value for a specific point in the river. This point must be a location where discharge measurements exist (Figure 1, white dots) for calibration of the the Strickler coefficient, K_s. This second calibration moment is performed using the same calibration data used for the 1D model.

2.4 Modelling calibration strategy

The flowchart outlining the calibration methodology is depicted in Figure 2. The calibration of the MAGE model uses minimal in-situ measurements obtained from the Sub-Institute of Hydrometeorology and Climate Change (SIHYMECC), a local Vietnamese agency. The locations for these measurements can be found as white dots in Figure 1. The measurement data, collected using a protocol in place for several years, include hourly river water level and velocity profiles gathered during campaigns of 48-hours every month from 2016 to 2020. Water level is directly measured with a scale, while discharge is derived from water level and depth-averaged velocity using the velocity index method (Chen et al., 2012). Considering the highly dynamic tidal conditions, the error in discharge estimation is approximately 15% with a minimum error of 150 m^3/s (Ruhl and Simpson, 2005).

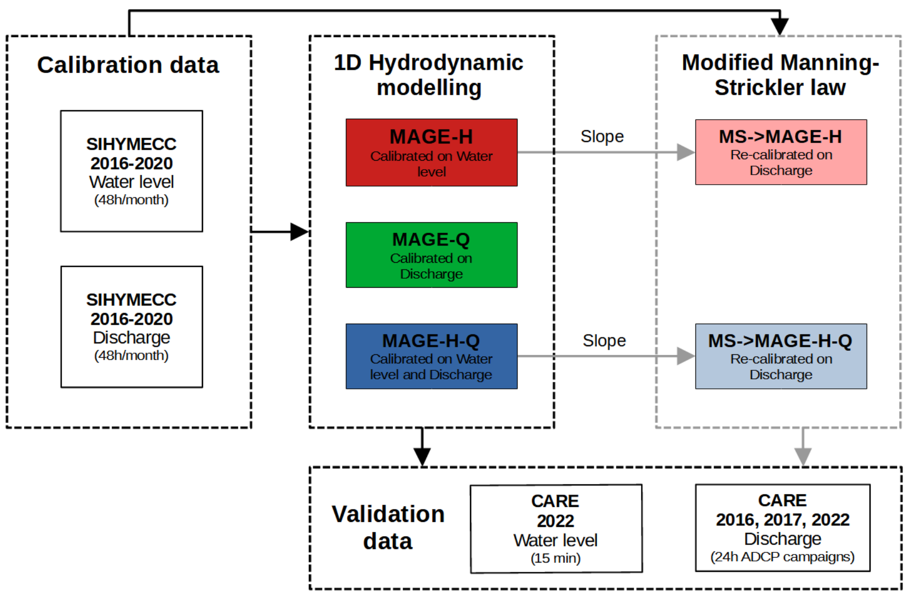

Figure 2. Flowchart outlining calibration and validation methods. Calibration data, provided by the Sub-Institute of Hydrometeorology and Climate Change (SIHYMECC), are from non-overlapping time periods from the validation data, which were supplied by the Center of Asian Research on Water (CARE).

Due to the quality limitations of discharge data available for calibration, three strategies are employed. Firstly, the MAGE model is calibrated solely using water level data and we denote it as MAGE-H (Figure 2, dark red). Secondly, MAGE is calibrated solely using discharge data, denoted as MAGE-Q (Figure 2, green). Finally, both water level and discharge data are used for calibration, resulting in MAGE-HQ (Figure 2, dark blue).

In an effort to improve discharge estimation, a modified MS law is coupled with the 1D model. The modification to the classic Manning-Strickler law enables negative slope values and thus, negative water discharge as it is observed in tidally forced rivers (see Section 2.3). This coupling involves feeding slope outputs from MAGE-H and MAGE-HQ into the modified MS law, which is then re-calibrated with discharge data, leading to MS->MAGE-H and MS->MAGE-HQ outputs (Figure 2, light red and blue, respectively).

For the first calibration moment, the Strickler coefficients in the MAGE model are calibrated with a sequential approach, starting from downstream to upstream in accordance with tide propagation. Initially, the Dongnai River is divided into three reaches: two before its confluence with the Saigon River and one between the confluence and the Tri An reservoir. Subsequently, the Saigon River is divided into seven reaches: five within the urban center and two between the city center and the Dau Tieng reservoir. The calibration exclusively utilizes data from SIHYMECC (Figure 2).

For each reach, a bounded Brent's algorithm (Grund, 1979; Brent, 2013) is employed to minimize a loss function. This is implemented using Python's minimize_scalar function from the Scipy library (Virtanen et al., 2020). Brent's algorithm is a numerical optimization method that combines the robustness of bracketing methods with the efficiency of interpolation techniques to find the minimum of a function. It is particularly effective for univariate optimization problems where the function is continuous but not necessarily smooth or differentiable. The loss function (Equation 4) is a weighted sum of the relative root mean square error for water level (rRMSE_H) and discharge (rRMSE_Q) across all measurement locations. The loss function $f(K_s)$ is formulated as:

$$f(K_s) = \sum_{i=1}^{n} C_i \cdot \left[\text{rRMSE}_H^i(K_s) + \text{rRMSE}_Q^i(K_s)\right], \tag{4}$$

$$\text{rRMSE}_H^i(K_s) = \sqrt{\frac{1}{m}\sum_{j=1}^{m}\left[\frac{H_{\text{true}}^j - H_{\text{model}}^j(K_s)}{H_{\text{true}}^j}\right]^2}, \tag{5}$$

$$\text{rRMSE}_Q^i(K_s) = \sqrt{\frac{1}{m}\sum_{j=1}^{m}\left[\frac{Q_{\text{true}}^j - Q_{\text{model}}^j(K_s)}{Q_{\text{true}}^j}\right]^2}, \tag{6}$$

where $n = 7$ denotes the number of SIHYMECC measurement locations, C_i represents the weight assigned to each measurement location, and rRMSE_H^i and rRMSE_Q^i are the water level and discharge rRMSE for location i, respectively. The superscript m represents each value in the time-series of water level and discharge. The weights (C_i) are constant values between 0 and 1, with higher importance assigned to measurement locations near the urban city center, as detailed in Table 1. This prioritization ensures that the model performance is given more significance around Ho Chi Minh City (HCMC), which is the focal point for flooding applications and other environmental impacts. By weighting the measurements in this manner, we aim to enhance the model's accuracy in areas that are most critical for urban planning and risk mitigation efforts.

Minimizing Equation 4 yields the optimal K_s value for a given reach within the MAGE code.

Table 1. Weights assigned to each measurement location for the calibration of the MAGE model.

Location	PC	BP	PA	NB	HA	CL	VS
Weight	0.8	1	1	0.8	0.8	0.8	0.5

For the second calibration moment, the Strickler coefficient of the MS law is calibrated against discharge data using the same algorithm as for the MAGE model. However, this calibration is performed separately for each location and focuses solely on discharge data. Therefore, the loss function to be minimized is exclusively Equation 6. The calibration of the modified MS equation constitutes a secondary phase of calibration on discharge, as the slope input is already derived from the calibrated MAGE model. It is important to note that the discharge data used in this phase of calibration is the same as the one used for the MAGE model calibration.

The models' validation is conducted using independent data from the Center of Asian Research on Water (CARE), which includes water level measurements every 15 minutes from October to December 2022 (Rodrigues do Amaral et al., 2023), as well as hourly discharge measurements from four 24-hour Acoustic Doppler Current Profiler (ADCP) campaigns in 2016, 2017, and 2022 (see figure 1, black crosses).

For the validation, two performance metrics are employed: rRMSE and the coefficient of determination, R^2. These metrics are computed as follows:

$$\mathrm{rRMSE} = \sqrt{\frac{1}{m}\sum_{j=1}^{m}\left[\frac{y^j_{\text{true}} - y^j_{\text{model}}}{y^j_{\text{true}}}\right]^2} \times 100, \tag{7}$$

$$\mathrm{R}^2 = 1 - \frac{\sum_{j=1}^{m}(y^j_{\text{true}} - y^j_{\text{model}})^2}{\sum_{j=1}^{m}(y^j_{\text{true}} - \bar{y}_{\text{true}})^2}. \tag{8}$$

where y_{true} and y_{model} are the measurement and the model output of the variable of interest, respectively, i.e. water level or discharge.

3 Results

Three calibration strategies were tested for the MAGE model: based on water level, discharge, or both parameters. For the coupled modified MS models (MS<-MAGE-H and MS<-MAGE-HQ), calibration used only discharge data. Calibration results for rRMSE and R^2 are shown in Figure B1 (Appendix B), while validation results for rRMSE are in Tables 3 and 2, and R^2 values in Figures C1 and C2 (Appendix C). Strickler coefficient values across the river are shown in Figure 3.

For the Saigon River, calibration using only water level measurements (MAGE-H, red in Figure 3) shows an increasing trend in Strickler coefficients (K_s) with distance from the reservoir, with some variability near the urban center (100-150 km). When using discharge data alone (MAGE-Q, green in Figure 3), K_s values increase further along most of the river. Including discharge data in the calibration (MAGE-HQ, blue in Figure 3) leads to higher K_s values across the river, except near the confluence.

Figure 4 shows validation data from the ADCP campaigns compared to model output, with the data being independent from the calibration dataset (see Figure 2). For the Saigon River, Strickler coefficients from MAGE-Q are higher than those from MAGE-HQ and MAGE-H, leading to larger discharge amplitudes (Figure 4). The rRMSE between ADCP data and model output improves significantly for MAGE-Q and MAGE-HQ calibrations (Table 2), indicating better model performance, despite the lower quality of discharge data. Table 2 shows that for the Saigon River, omitting water level data improves rRMSE, while for the Dongnai River, using discharge data yields similar performance to water level calibration alone. MAGE-HQ outperforms MAGE-H and MAGE-Q, as discharge-only calibration leads to overestimation. However, all models show similar behavior for the asymmetric tide (2016 ADCP campaign, Figure 4c), where the modified MS model provides no significant improvement. The MS coupling slightly alters net outflow results (Figure 4).

For operational discharge estimation, accuracy is crucial. Table 2 shows that coupling the modified MS equation reduces the rRMSE of the MAGE model's discharge output by 50% during the symmetric tide (2016) and by 20% during the asymmetric tide (2017) on the Saigon River. However, errors remain between 31% and 51%, highlighting the challenges of discharge

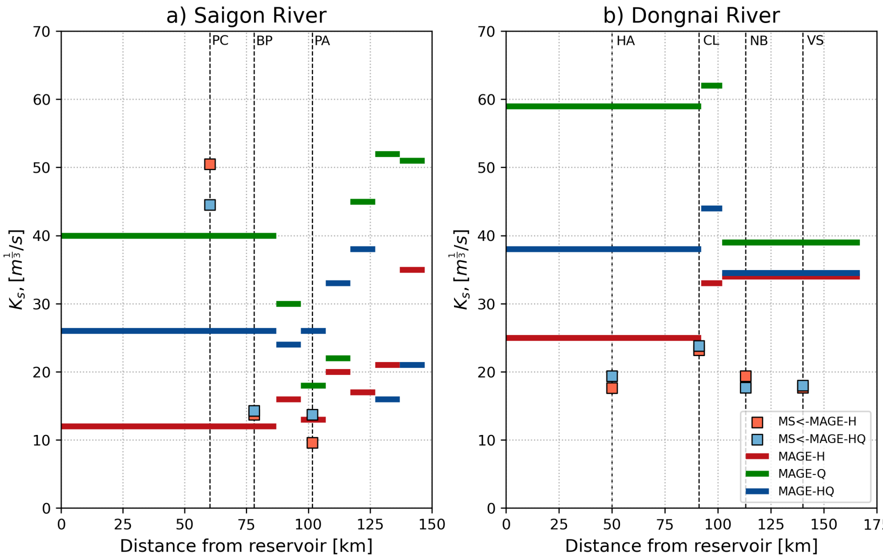

Figure 3. Strickler coefficients obtained from the calibration of the MAGE model. Solid lines in red, green and blue correspond to MAGE-H, MAGE-Q and MAGE-HQ. The blue and orange squares correspond to the MS<-MAGE-HQ and MS<-MAGE-H at the locations of SIHYMECC measurements.

Table 2. Validation results for rRMSE [%] between model discharge and ADCP campaigns. The ADCP data was not used for the calibration efforts and thus, model output and validation data are fully independent.

	MAGE-H	MAGE-Q	MAGE-HQ	MS<-MAGE-H	MS<-MAGE-HQ
PC 2016	-148	-62	-75	38	31
PC 2017	-148	-68	-78	49	51
HA 2016	31	36	23	43	52
HA 2022	-38	47	29	36	40

estimation in dynamic tidal rivers. For the Dongnai River, the coupling yields similar or slightly worse results than MAGE alone.

Introducing discharge data in the calibration slightly increases water level rRMSE at most stations (Table 3), but has little impact on rRMSE between validation data and model output. The rRMSE difference between MAGE-H and MAGE-Q is consistently under 10%, and between MAGE-H and MAGE-HQ, it remains below 5%. Regardless of the calibration approach, the model accurately captures water level dynamics, with R^2 values exceeding 0.80 at all stations (Figure C1, Appendix B).

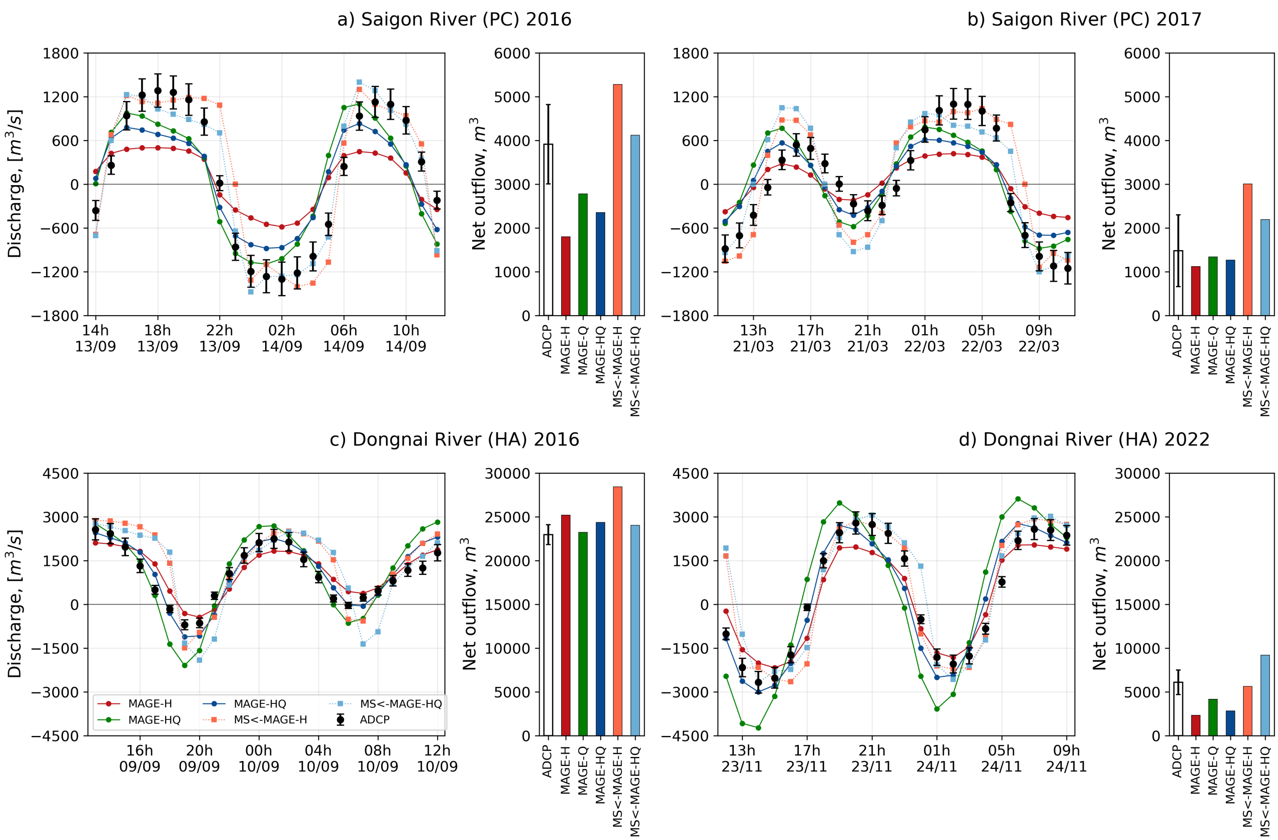

Figure 4. Discharge time-series and net outflow comparison between ADCP campaigns and model output. Black dots with uncertainty bar represent the ADCP measurements. Solid lines with dots represent MAGE-H, MAGE-Q and MAGE-HQ in red, green and blue, respectively. Dashed lines with squares represent the MS<-MAGE-H and MS<-MAGE-HQ in orange and blue, respectively. a) and b) Campaigns of September 2016 and March 2017, at the Phu Cuong (PC) location in the Saigon river during a symmetric and asymmetric tide, respectively. c) and d) Campaigns of September 2016 and November 2022, at the Hoa An (HA) location in the Dongnai river during an asymmetric and symmetric tide, respectively.

4 Discussion and Conclusions

This study explores calibration strategies for hydrodynamic modeling of dynamic tidal rivers, specifically the Saigon and Dongnai rivers. The three MAGE model calibration approaches—based on water level, discharge, or both—provide valuable insights into model behavior under data scarcity. Additionally, coupling the modified Manning-Strickler (MS) equation with the MAGE model offers a novel method to improve discharge estimation for operational purposes, though results vary across river systems.

The model accurately simulated water levels and discharges in the Dongnai River. However, calibration in the Saigon River was more challenging due to the system's complexity, with significant tidal discharges and low net watershed inflows. Intro-

Table 3. Validation results for rRMSE [%] between model water level and water level measurements.

	MAGE-H	MAGE-Q	MAGE-HQ
H1	30	38	30
H2	28	32	27
H3	25	27	24
LG	25	32	30
HA	31	41	33
NB	17	21	18

ducing discharge data from measured vertical velocity profiles improved discharge estimation. However, the effectiveness of this approach varied, as the Dongnai River showed comparable performance across calibration strategies.

Modeling challenges arise from balancing simplicity for operational use with accurately representing physical phenomena. For instance, the MAGE model fails to capture tidal wave attenuation, with minimal improvements from different calibration strategies. However, coupling the MS law with a second calibration step significantly enhances discharge accuracy, as shown by validation efforts. Despite this, the one-dimensional nature of the model isn't the limiting factor; using a higher-dimensional model would be impractical due to the need for more data, such as velocity fields, which are scarce in regions like the one studied.

Calibration results show distinct variations in Strickler coefficient (K_s) values along the river, reflecting channel roughness. These variations depend on the calibration strategy and the implementation of modified MS coupling. A higher K_s indicates smoother channel conditions and faster flow velocities, while a lower K_s suggests rougher conditions and slower velocities. In our study, K_s values ranged from 10 $\mathrm{m}^{1/3}$/s (rough) to 50 $\mathrm{m}^{1/3}$/s (smooth), highlighting substantial variability in channel roughness. These variations underscore the challenges of modeling tidally influenced rivers. Asymmetrical flow patterns in the Saigon and Dongnai rivers are influenced by tidal amplitudes, morphology, and coastal features, with K_s's effect on discharge varying by tidal phase and river response. This emphasizes the importance of timing in calibration and validation data collection.

While the model provides good estimates of discharge dynamics within the Saigon-Dongnai system, further refinement is needed, particularly with upstream boundary conditions and lateral inflows. Accurate upstream discharge values from the reservoirs are essential for model precision. As a 1D model, it requires net discharge as an input, preventing direct derivation of net discharge from the model's results. The lack of data of lateral inflows from irrigation and urban canals is seen as an important issue with the modeling efforts presented here. The possibility to couple a hydrological model and incorporating lateral inflows would increase complexity with limited improvement in accuracy.

Recent interest in using advanced statistical and machine learning techniques to improve hydrodynamic model calibration faces challenges in data-scarce regions, where large datasets are often unavailable. However, less data-hungry Bayesian methods offer a robust framework for parameter estimation and improving predictive accuracy in hydrodynamic models (Mendez Rios et al., 2023). Future research could explore the potential of these methodologies for dynamic tidal river systems, advancing predictive capabilities. Additionally, considering the impact of canal networks and coupling the model with an advection-dispersion model like AdisTS (Launay et al., 2019) could provide valuable insights into flood events and pollutant dispersion.

The methodology presented in this study extends beyond the Saigon-Dongnai river system and offers a practical framework for hydrodynamic modeling in data-scarce, tide-dominated river networks worldwide. Many deltaic and estuarine regions, particularly in developing countries, face similar challenges due to limited monitoring infrastructure, making traditional data-intensive approaches impractical. Our study demonstrates that coupling a simple flow law to improve the calibration of a 1D model with minimal in-situ data provides a viable alternative to more computationally demanding methods. Furthermore, the model's ability to simulate a full year in just five minutes makes it particularly suitable for long-term scenario testing, sensitivity analyses, and operational forecasting applications. Future research could explore the integration of remote sensing data or machine learning techniques to further enhance model calibration and expand its applicability to other poorly gauged, tide-influenced river networks.

Code and data availability. The MAGE 1D hydrodynamic model is developped by INRAE (French Research Institute for Agriculture, Food and Environment), its source code is written in FORTRAN and can be downloaded here: https://gitlab.irstea.fr/jean-baptiste.faure/MAGE [accessed 4. Apr. 2024]. The data and related documentations that support the findings of this study are openly available in DataSuds repository (IRD, France) at https://doi.org/10.23708/KLQMSR. Data reuse is granted under CC-BY license.

Appendix A: MAGE model boundary conditions

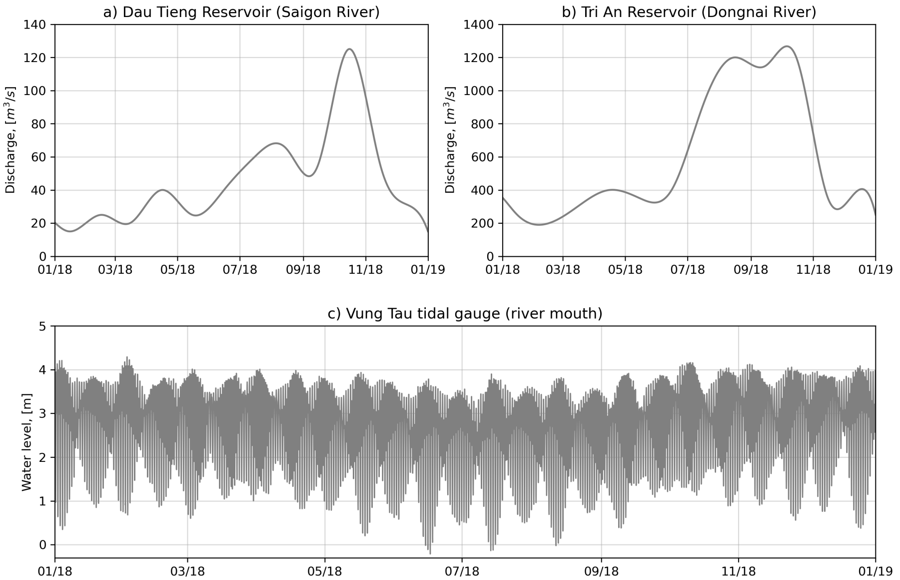

Figure A1. Boundary conditions used in MAGE model: example for the year 2018. a) Upstream boundary condition for the Saigon river branch: discharge at the Dau Tieng reservoir. b) Upstream boundary condition for the Dongnai river: discharge at the Tri An reservoir. c) Downstream boundary condition at the mouth of the river Dongnai: water level at the Vung Tau tidal gauge.

Appendix B: Calibration results: rRMSE and R^2

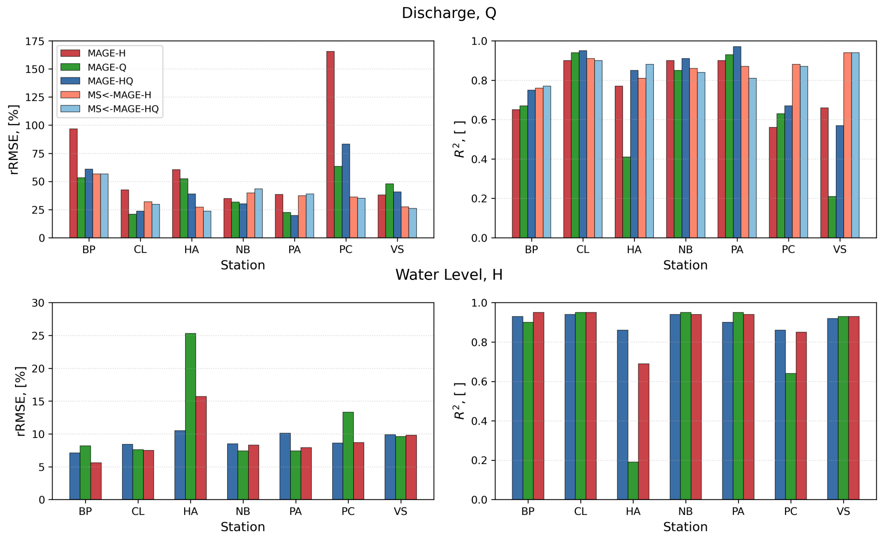

Figure B1. Calibration results for the MAGE model and for the MS<-MAGE coupling. rRMSE and R^2 between model output and calibration data from the SIHYMECC measurement locations are shown. Dark red, green and dark blue bars represent the MAGE-H, MAGE-Q and MAGE-HQ results. Light red and light blue bars represent the MS<-MAGE-H and MS<-MAGE-HQ results.

Appendix C: Validation results: R^2

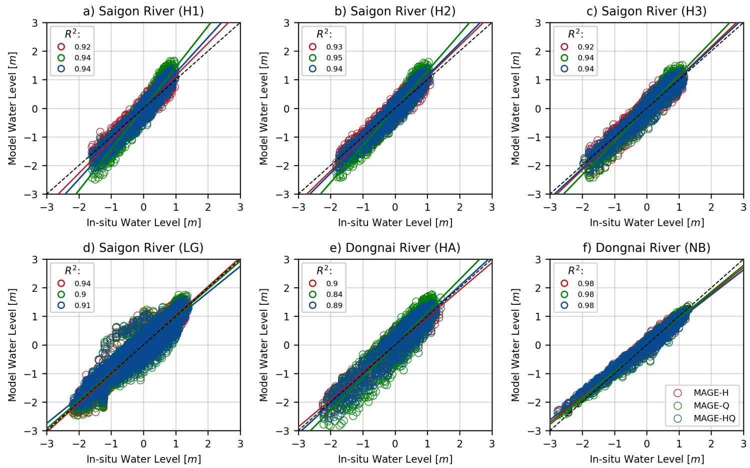

Figure C1. Linear regression lines and R^2 values between CARE water level measurements and model water level output. The black dashed line represents the $y = x$ line. Red, green and blue circles represent the MAGE-H, MAGE-Q and MAGE-HQ results. Solid lines represent linear regressions for each model with the same color code. a) to d) show results for Saigon locations H1, H2, H3 and LG. e) and f) show results for the locations in the Dongnai river HA and NB, respectively.

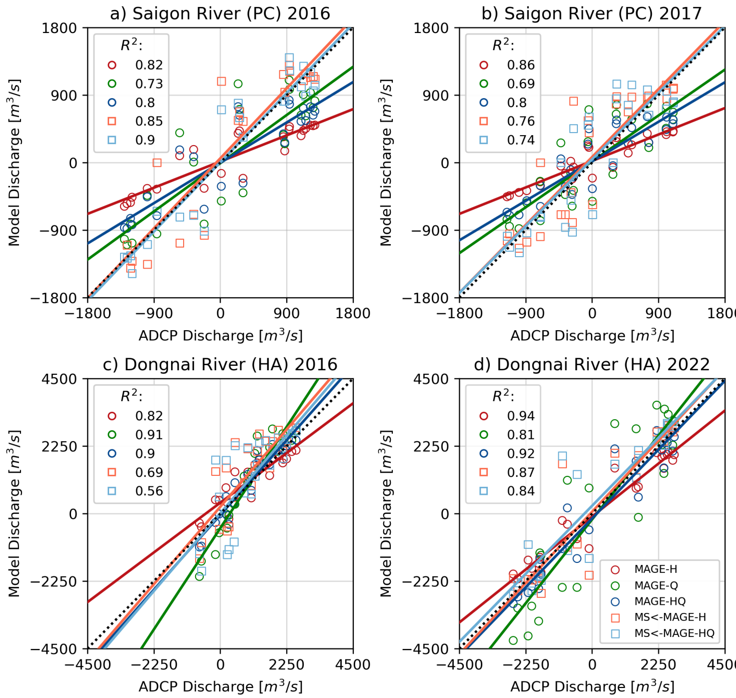

Figure C2. Linear regression lines and R^2 values between ADCP discharge and model discharge. The black dotted line represents the $y = x$ line. Red, green and blue circles represent the MAGE-H, MAGE-Q and MAGE-HQ results and blue and orange squares the MS<-MAGE-H and MS<-MAGE-HQ results. Solid lines represent linear regressions for each model with the same color code as the circles and squares. a) and b) ADCP campaigns of September 2016 and March 2017, at the Phu Cuong (PC) location in the Saigon river during a symmetric and asymmetric tide, respectively. c) and d) ADCP campaigns of September 2016 and November 2022, at the Hoa An (HA) location in the Dongnai river during an asymmetric and symmetric tide, respectively.

Author contributions. Conceptualization, investigation: FRdA and BC; data collection and curation: FRdA and TNT; writing and editing: FRdA; reviewing and supervision: BC, NG, TP and TAT.

Competing interests. The authors have declared that no competing interests exist.

Acknowledgements. This research was conducted thanks to the financial, technical and human support of the CARE-RESCIF initiative (http://carerescif.hcmut.edu.vn/) within the International Joint Laboratory LECZ-CARE. We would like to thank Dr. Nguyen Truong An for providing the bathymetric data of the River Saigon and River Dongnai. We would also like to acknowledge Mr. Jerard Jardin from the University of Hawaii Sea Level Center for his invaluable work maintaining the Vung Tau tidal gauge.

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