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

Francisco Rodrigues do Amaral[1], Benoît Camenen[2], Tin Nguyen Trung[3], Tran Anh Tu[4], Thierry Pellarin[1], and Nicolas Gratiot[1,3]

[1]Université Grenoble Alpes, CNRS, INRAE, IRD, Grenoble INP, IGE, Grenoble, France
[2]RiverLy, INRAE, Villeurbanne, France
[3]CARE, Ho Chi Minh City University of Technology (HCMUT), VNU-HCM, Ho Chi Minh City, Vietnam
[4]Vietnam National University-Ho Chi Minh City (VNU-HCM), Thu Duc City, Ho Chi Minh City, Vietnam

Correspondence: Francisco Rodrigues do Amaral (francisco.amaral@univ-grenoble-alpes.fr)

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~~is explored. Calibration efforts reveal distinct trends~~. Calibration results reveal distinct spatial variations in friction coefficients along the river ~~. The introduction of indirectly measured discharge data significantly improves~~ system, highlighting the importance of localized adjustments. Incorporating this calibration technique significantly enhances model performance, ~~particularly for~~ reducing discharge rRMSE by 27% to 44% in the Saigon River ~~branch. Validation against independent measurements demonstrates promising results, with the coupling of the modified MS equation providing improved discharge estimates~~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 ~~and relies on continuous water level sensor data. Their discharge estimates are limited to the duration of their measurement campaign from 2017 to 2018.~~ 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. demonstrate the challenges of operating a develop and validate a calibration methodology for improving 1D hydrodynamic model with minimal data 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 the Mage code 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 of friction coefficients poses particular challenges for tidal rivers due to the downstream water level's control over flow dynamics. The River Saigon presents additional difficulties, including the absence of reliable and open-access data on upstream net discharge and the potential impact of extensive canals within the HCMC megalopolis on flow dynamics. 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. AdditionallyFinally, a modified Manning-Strickler (MS) law was coupled with the hydrodynamic model to improve discharge estimation.

In conclusion, this study provides valuable insights and practical implications for water resource management and decision-making in data-scarce estuarine systems. The long time-series of estimated water levels and discharge data are made available in open access, offering a critical resource for both scientific and operational use.

2 Materials and Methods

In this study~~we consider three strategies for calibrating a 1D hydrodynamic model over a complex tidal estuary located in~~ , 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. ~~The hydrodynamic model under consideration is the Mage code, which will be further presented in sub-section 2.2. The flowchart outlining the methodology is depicted in Figure 2.~~

~~Flowchart outlining calibration and validation methods.~~ 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.

~~The calibration of the Mage model uses minimal in-situ measurements obtained from the Sub-Institute of Hydrometeorology and Climate Change (SIHYMECC)~~ Second, to address data limitations and enhance discharge estimation, ~~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 monthly campaigns of 48-hours 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).~~

~~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. Secondly, Mage is calibrated solely using discharge data, denoted as MAGE-Q. Finally, both water level and discharge data are used for calibration, resulting in MAGE-HQ. In an effort to improve discharge estimation, a modified MS law is coupled~~ we integrate a modified Manning-Strickler (MS) law 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.~~

~~Although coupling a 1D hydrodynamic model with a simplified flow law, such as~~ 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 ~~Manning-Strickler equation, may initially seem counter-intuitive, it provides essential insights into the dynamics of estuarine rivers. The use of different Strickler coefficients for water levels and discharge, allows for a more detailed calibration of specific components of the system. This approach can enhance the understanding of system behavior by isolating the effects of discharge. It is important to note that recalibrating the MS equation using results from the 1D model aims to refine discharge estimations, despite the fixed water levels that should vary for a modified Strickler coefficient. This refinement can improve operational predictions (as shown in Section 3) for processes such as pollutant advection, nutrient residence times, and salt intrusion. Ultimately, this methodology, when applied with caution, helps to bridge the gap between simplified and detailed modeling approaches, providing a balance between computational efficiency and modelaccuracy.~~

The models' validation is conducted using 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 2016same discharge data as the 1D model, 2017, and 2022 (see figure 1, black crosses)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: MageMAGE

The model for the Saigon-Dongnai river system was constructed utilizing the PamHyr interface presently written in Java and soon to be accessible as a Python interface (Rouby et al., 2024). 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. Subsequently, numerical modeling was conducted using the Mage code (Souhar and Faure, 2009).

The Mage code solves the 1D Barré-de-Saint-Venant equations 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:

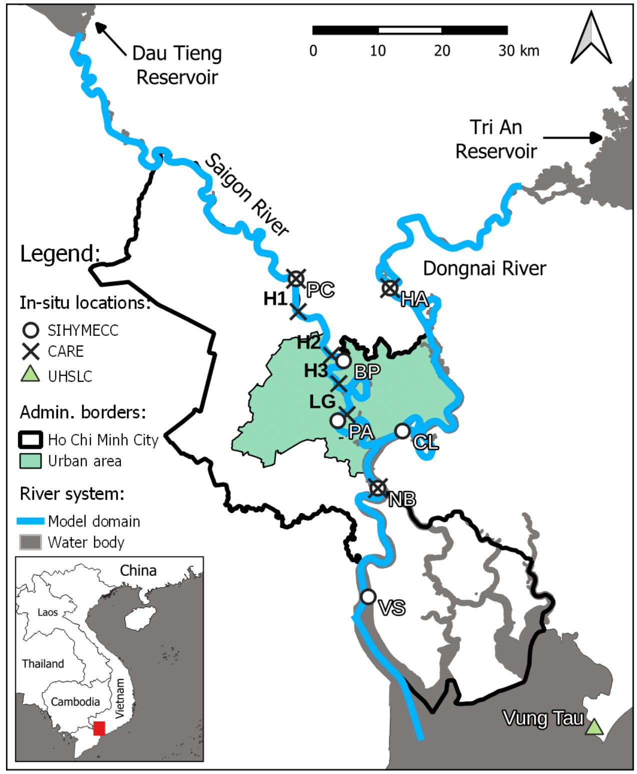

Figure 1. Map of the study area. The estuary water bodies (grey) and the ~~Mage~~ MAGE model domain (blue) with the Dongnai river (right) and its Saigon river branch (left) can be seen. Locations of river measurements from the Sub-Institute of Hydrometeorology and Climate Change (SYHIMECC, white dots) 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.

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

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

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 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.

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 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

Given Mage's challenges The MAGE model has difficulty in accurately predicting both water level and river discharge (Camenen et al., 2023)in the Saigon branch (Camenen et al., 2023) especially within the framework of data scarcity. Hence, we opted to couple this model with a discharge estimation approach 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 a stage-fall-discharge (SFD) rating curve adapted from the general Manning-Strickler law(Eq. 3): MAGE feeds into the modified MS law. This law is formulated as follows:

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

with Q representing the water discharge [m^3s^{-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 MAGE around the point where discharge estimation from the MS law is desired. All variables (S, Aw, R_h) except K_s are as outputted by the Mage model. However, this 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 , as the equation requires (Figure 1, white dots) for calibration of the the Strickler coefficient, K_s. Consequently, this integration of a This second calibration moment is performed using the same calibration data used for the 1D hydrodynamic modeland a simplified flow law only has an interest at locations where SIHYMECC measurements exist (Figure 1, white dots). model.

2.4 Modelling calibration strategy

The calibration of 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).

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 follows 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

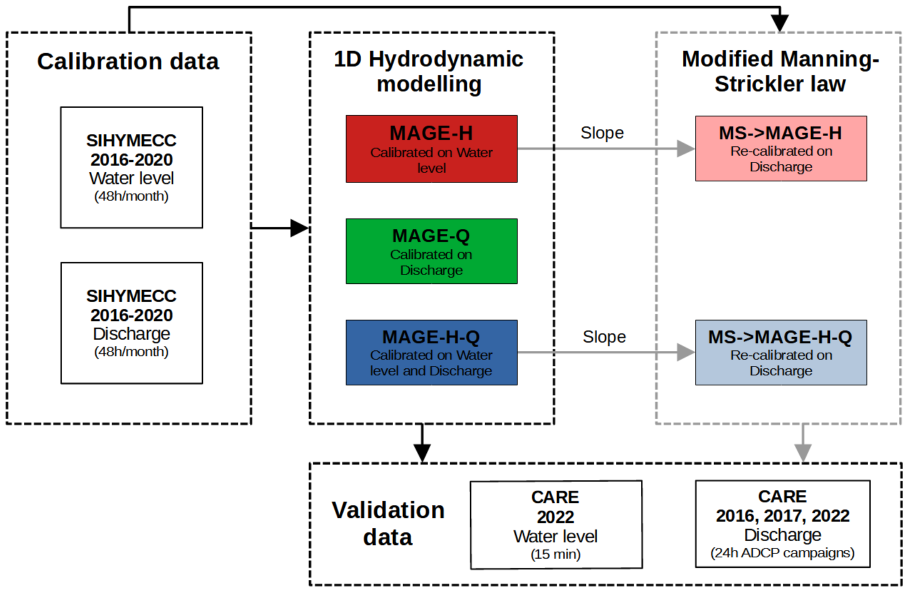

Figure 2. Flowchart outlining calibration and validation methods. Calibration data, provided by the Sub-Institute of Hydrometeorology and Climate Change (SIHYMECC), are from non-overlapping time periods from the validation data, which were supplied by the Center of Asian Research on Water (CARE).

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~~ MAGE code.

Table 1. Weights assigned to each measurement location for the calibration of the ~~Mage~~ 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 ~~modified MS equation~~second calibration moment, the Strickler coefficient of the MS law is calibrated against discharge data using the same algorithm as for the ~~Mage~~ 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~~ MAGE model. It is important to note ~~the the~~ that the discharge data used in this phase of calibration is the same as the one used for the ~~Mage~~ MAGE model calibration. ~~Additionally, it is important to reinforce that the modified MS equation can only be applied pointwise, meaning that discharge output is available only at the exact locations where the equation is calibrated, i.e., locations where discharge data is available, notably at the SIHYMECC locations.~~

~~The validation of the models utilizes independent measurements from CARE (Figure 2) . Two~~ 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:

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

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

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: calibration solely~~ MAGE model: based on water level, ~~solely on~~ discharge, or ~~on both parameterssimultaneously~~both parameters. For the coupled modified MS ~~equation models , namely~~ models (MS<-MAGE-H and MS<-MAGE-HQ~~, calibration was conducted exclusively using~~), calibration used only discharge data. Calibration results for rRMSE and R^2 ~~can be found~~ are shown in Figure B1 ~~in Appendix B. For the validation results , the relative Root Mean Square Error (rRMSE) metric is presented~~ (Appendix B), while validation results for rRMSE are in Tables 3 and 2, ~~while the coefficient of determination (~~and R^2 ~~) can be referenced~~ values in Figures C1 and C2 ~~in Appendix C. The resulting~~ (Appendix C). Strickler coefficient values across the river ~~extent are illustrated~~ are shown in Figure 3.

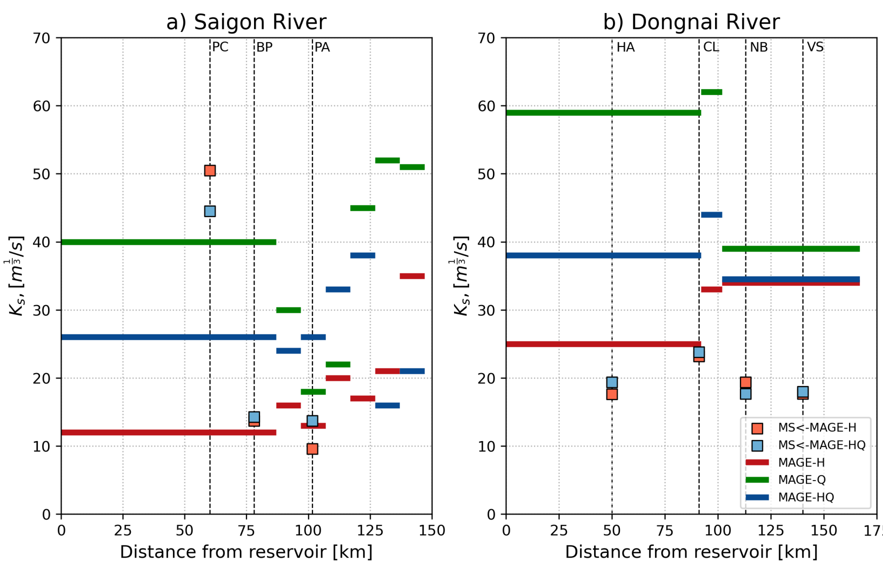

Figure 3. Strickler coefficients obtained from the calibration of the ~~Mage~~ MAGE model. Solid lines in red, green and blue correspond to MAGE-H, MAGE-Q and MAGE-HQ. The blue and orange squares correspond to the MS<-MAGE-HQ and MS<-MAGE-H at the locations of SIHYMECC measurements.

For the Saigon River, ~~when calibrating the model using~~ calibration using only water level measurements ~~only~~ (MAGE-H, ~~depicted in~~ red in Figure 3) ~~,~~ shows an increasing trend in Strickler coefficients (K_s) ~~exhibit an increasing trend as~~ with distance from the reservoir~~increases~~, with some variability ~~around the urban city center (100 kmto 150 km~~near the urban center (100-150 km). When ~~calibrating the model~~ using discharge data ~~only~~ alone (MAGE-Q, ~~in~~ green in Figure 3), K_s values ~~experience further increments for most parts~~ increase further along most of the river. ~~Furthermore, introducing discharge data into the calibration process~~ Including discharge data in the calibration (MAGE-HQ, ~~shown in~~ blue in Figure 3) ~~results in increased~~ leads to higher K_s values ~~throughout~~ across the river, except near the confluence.

Figure 4 ~~presents~~ shows validation data from the ADCP campaigns ~~plotted against model output. These data, distinct from those employed in model calibration, stand as fully~~ compared to model output, with the data being independent from the

~~model's output~~ calibration dataset (see Figure 2). For the Saigon River, ~~the Strickler coefficients were found to be larger for the~~ Strickler coefficients from MAGE-Q ~~calibration compared to the~~ are higher than those from MAGE-HQ and MAGE-H~~calibrations. This results in~~, leading to larger discharge amplitudes ~~, as indicated by the red, blue, and green curves in Figure 4. Moreover, the~~ (Figure 4). The rRMSE between ADCP ~~measurements~~ data and model output ~~substantially decreases for the~~ improves significantly for MAGE-Q and MAGE-HQ ~~calibration (refer to~~ calibrations (Table 2), indicating ~~a significant improvement in model capability~~ better model performance, despite the lower quality of discharge data~~compared to water level measurements~~. Table 2 ~~also demonstrates that calibrating without utilizing~~ shows that for the Saigon River, omitting water level data ~~results in an improvement in rRMSEfor the Saigon river. However, this is not the case~~ improves rRMSE, while for the Dongnai ~~river as introducing discharge data into the calibration effort provides comparable performance to using only water level measurements. Table 2 shows that~~ River, using discharge data yields similar performance to water level calibration alone. MAGE-HQ ~~calibration yields better results than~~ outperforms MAGE-H and MAGE-Q~~as calibrating using discharge data only~~, as discharge-only calibration leads to overestimation. However, all models ~~are behaving similarly~~ show similar behavior for the asymmetric tide (~~ADCP campaign of 2016~~2016 ADCP campaign, Figure 4c)~~. In this case~~, where the modified MS model ~~does not bring any notable improvements. In terms of net outflow, the modified MS coupling may slightly modify~~ provides no significant improvement. The MS coupling slightly alters net outflow results (Figure 4).

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

For operational ~~purposes, achieving the most accurate discharge estimationis crucial regardless of the method~~discharge estimation, accuracy is crucial. Table 2 ~~reveals~~ shows that coupling the modified MS equation reduces the rRMSE of the ~~Mage model~~MAGE model's discharge output by ~~half~~ 50% during the symmetric tide ~~of the~~ (2016~~campaign and by approximately~~) and by 20% during the asymmetric tide ~~of the~~ (2017~~campaign for~~) on the Saigon River. However, errors ~~still range~~ remain between 31% and 51%, ~~underscoring the challenge of accurately estimating discharge in such~~ highlighting the challenges of discharge estimation in dynamic tidal rivers. ~~Conversely~~For the Dongnai River, the coupling ~~provides~~ yields similar or slightly worse results than ~~Mage for the Dongnai River~~MAGE alone.

Introducing discharge data in the calibration ~~efforts marginally impacts water level output, resulting in slight increases in rRMSE values~~ slightly increases water level rRMSE at most stations (Table 3)~~. However, this calibration approach does not significantly affect the rRMSE values~~, but has little impact on rRMSE between validation data and model output. The rRMSE difference between MAGE-H and MAGE-Q is consistently ~~below~~ under 10%~~. Additionally, the rRMSE~~, and between MAGE-H and MAGE-HQ~~exhibits minimal differences, always~~, it remains below 5%. ~~Consequently, regardless~~ Regardless

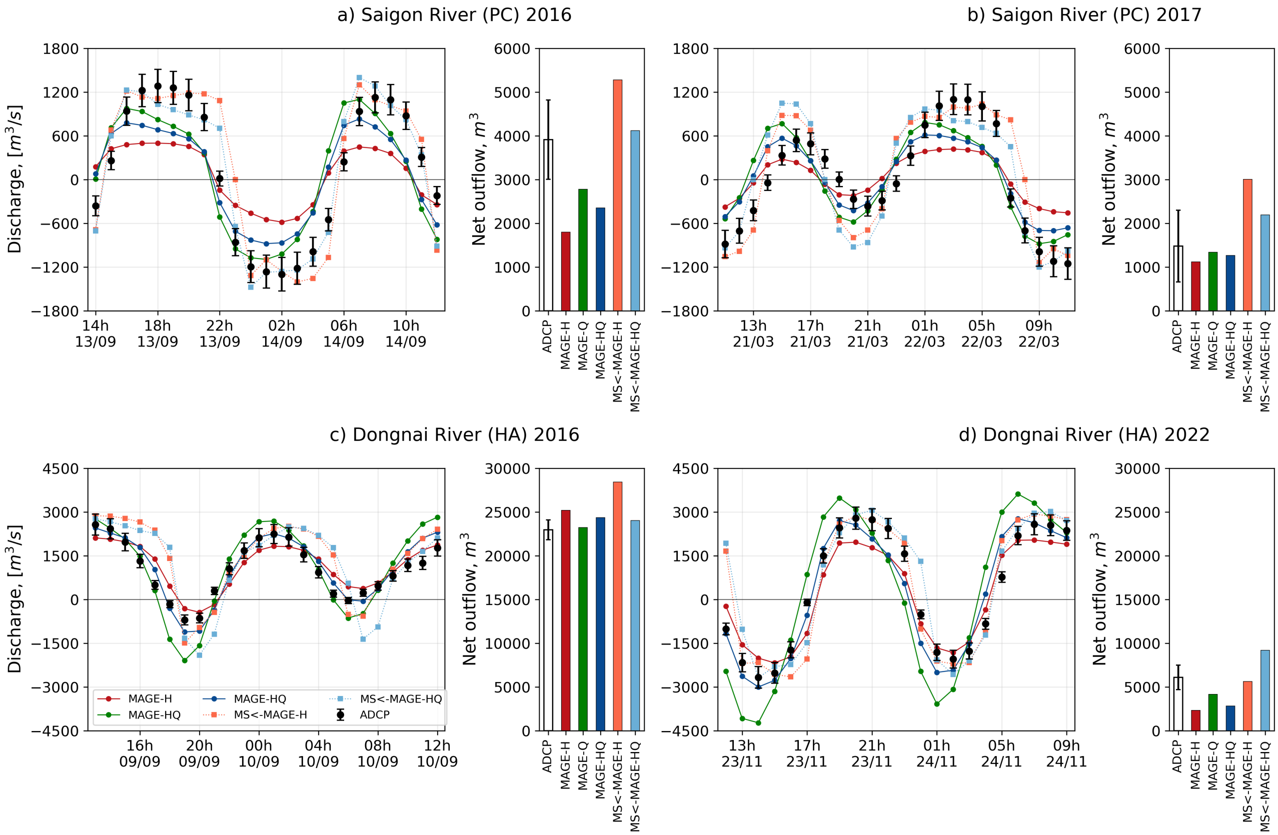

Figure 4. Discharge time-series and net outflow comparison between ADCP campaigns and model output. Black dots with uncertainty bar represent the ADCP measurements. Solid lines with dots represent MAGE-H, MAGE-Q and MAGE-HQ in red, green and blue, respectively. Dashed lines with squares represent the 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.

of the calibration approach, the model ~~effectively reproduces the dynamic nature of water level fluctuations, which is also demonstrated by the~~ accurately captures water level dynamics, with R^2 values exceeding 0.80 at ~~every measurement station (refer to Figure C1in~~ all stations (Figure C1, Appendix B).

4 Discussion and Conclusions

~~The calibration strategies employed in this study provide insights into the~~ This study explores calibration strategies for hydrodynamic modeling of dynamic tidal rivers, ~~particularly~~ specifically the Saigon and Dongnai rivers~~in Southeast Asia~~. The three ~~calibration strategies tested for the Mage model , focusing~~ MAGE model calibration approaches—based on water level,

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

discharge, or both~~parameters simultaneously, offer valuable understanding of~~ —provide valuable insights into model behavior under ~~varying calibration conditions with scarce data~~ data scarcity. Additionally, ~~the coupling of~~ coupling the modified Manning-Strickler (MS) equation with the ~~Mage model presents a novel approach to enhance~~ MAGE model offers a novel method to improve discharge estimation for operational purposes, ~~albeit with mixed results across different~~ though results vary across river systems.

~~In this tidal-dominated system, the methodology for calibrating friction coefficients involved starting from downstream reaches and then proceeding to calibrate upstream reaches following tidal wave propagation. The model yielded very accurate results for both~~ The model accurately simulated water levels and discharges in the ~~Dong-Nai~~ Dongnai River. However, ~~achieving a satisfactory fit for both datasets~~ calibration in the Saigon River ~~proved more challenging . The calibration effort was notably affected by the system'~~was more challenging due to the system's complexity, ~~characterized by~~ with significant tidal discharges and low net ~~discharges originating from the watershed . Notably, the introduction of~~ watershed inflows. Introducing discharge data from measured vertical velocity profiles ~~significantly impacts model performance, leading to improved accuracy in discharge estimation, especially for the Saigon River~~improved discharge estimation. However, the effectiveness of this approach ~~varies, with~~ varied, as the Dongnai River ~~demonstrating~~ showed comparable performance across ~~different~~ calibration strategies.

Modeling ~~efforts are challenging due to the tradeoff between model~~ challenges arise from balancing simplicity for operational use ~~and the accurate representation of~~ with accurately representing physical phenomena. For ~~example, the Mage model does not effectively~~ instance, the MAGE model fails to capture tidal wave attenuation, ~~and~~ with minimal improvements from different calibration strategies~~result in only negligible improvements~~. However, ~~when we couple the Manning-Strickler~~ coupling the MS law with a second calibration step ~~, the improvements become significant. This operational trick~~ significantly enhances discharge accuracy, as ~~validation efforts demonstrate. Nonetheless~~shown by validation efforts. Despite this, the one-dimensional nature of the model ~~is not~~ isn't the limiting factor~~in this case. Using~~ ; using a higher-dimensional model would be impractical ~~, as calibration would require~~ due to the need for more data, ~~including higher-dimensional data~~ such as velocity fields, which are ~~hardly available in data-scarce~~ scarce in regions like the one ~~under study~~studied.

~~The calibration results reveal distinct trends~~ Calibration results show distinct variations in Strickler coefficient ~~,~~ (K_s~~,~~) values along the river~~extent, reflecting variations in~~ , reflecting channel roughness. ~~We observe significant variations in K_s~~

values depending These variations depend on the calibration strategy and after implementing the implementation of modified MS coupling. The Strickler coefficient represents the hydraulic roughness of the channel bed, influencing water levels, flow velocity and thus discharge. For instance, a higher Strickler coefficient A higher K_s indicates smoother channel conditions , allowing for and faster flow velocities, while a lower coefficient K_s suggests rougher conditions , resulting in and slower velocities. In our study, we observed a range of, K_s , values from a very rough value of values ranged from 10 $m^{1/3}$/s to a smoother (rough) to 50 $m^{1/3}$/s , indicating (smooth), highlighting substantial variability in channel roughnessalong the river network. These variations illustrate underscore the challenges of modeling tidally influenced river systems. The Strickler coefficient influences discharge rates during both rising and falling tidal phases, with higher coefficients typically resulting in increased discharges. The rivers. Asymmetrical flow patterns in the Saigon and Dongnai rivers exhibit asymmetrical flow patterns due to are influenced by tidal amplitudes, morphology, and coastal features. The impact of the , with $K_s$value on discharge varies with the dominant 's effect on discharge varying by tidal phase and river responseto tidal forcing, emphasizing . This emphasizes the importance of timing in data collection for calibration and validation . Moreover, the physical behavior of the river may vary at different tidal phases, affecting the Strickler coefficient. data collection.

The validation of model outputs against independent measurements underscores the importance of incorporating discharge data for enhancing model capability. Despite the challenges associated with accurately estimating discharge in dynamic tidal rivers, the Mage model and the MS<-MAGE coupling demonstrate promising results, especially when considering the operational implications of discharge estimation. The impact of calibration efforts on water level output highlights the trade-off between accuracy and simplicity in hydrodynamic modeling. While introducing discharge data may marginally affect water level output, the model retains its ability to capture the dynamic fluctuations in water level, as evidenced by high coefficient of determination (R^2) values across measurement stations.

While the current model provides sufficiently model provides good estimates of discharge dynamics within the Saigon-Dongnai system, further refinements are refinement is needed, particularly regarding the use of accurately measured with upstream boundary conditions and lateral inflows. Accurate upstream discharge values from the reservoirs are crucial essential for model precision. Given that the model is one-dimensional (As a 1D), it inherently model, it requires net discharge as a boundary condition an input, preventing the direct derivation of net discharge directly from the model''s results. Consequently, the primary goal of the modeling effort is to obtain more precise instantaneous discharge and water level estimates, incorporating tidal dynamics throughout the entire river system. This objective has been successfully achieved, and the resulting time series data can provide valuable insights to reservoir managers controlling the river system. Additionally, the modeling effort can be significantly improved if reservoir discharge data are accurately measured and shared with the scientific community. Tidal gauge data, such as those from the Vung Tau station (coastal boundary condition), are already available in near real-time and openly accessible through the University of Hawaii Sea Level Center's website. Therefore, it is imperative that reservoir discharge data are similarly monitored and made publicly available, as they play a crucial role in improving modeling efforts . 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.

~~In recent years, there has been growing interest in leveraging~~ Recent interest in using advanced statistical and machine learning techniques to ~~enhance the calibration of hydrodynamic models. However, this is not possible~~ improve hydrodynamic model calibration faces challenges in data-scarce regions~~as these methods rely on large amounts of data. Similarly, machine learning algorithms and AI systems require the leveraging of large datasets for automating and optimizing the calibration process. On the other hand,~~ , where large datasets are often unavailable. However, less data-hungry Bayesian methods offer a robust framework for ~~calibrating hydrodynamic models (Mendez Rios et al., 2023), thereby improving~~ parameter estimation and ~~predictive accuracy. Integrating these techniques with traditional calibration approaches for 1D models like Mage holds great potential for improving model performance and reducing uncertainty in predictions~~improving predictive accuracy in hydrodynamic models (Mendez Rios et al., 2023). Future research ~~endeavors~~ could explore the ~~applicability and effectiveness of such methodologies in the context of~~ potential of these methodologies for dynamic tidal river systems, ~~thereby advancing our understanding and predictive capabilitiesin hydrodynamic modeling. In future modelling works, the consideration of canal network impact on the rivers is also recommended. Subsequently, the model could be used to analyze significant flood events. Coupling the model~~ advancing predictive capabilities. Additionally, considering the impact of canal networks and coupling the model with an advection-dispersion model like AdisTS ~~developed at INRAE (Launay et al., 2019) would also be beneficial in understanding pollutant dispersionin this complex system~~(Launay et al., 2019) could provide valuable insights into flood events and pollutant dispersion.

~~Overall, this study sheds light on the complexities of calibrating hydrodynamic models~~ The methodology presented in this study extends beyond the Saigon-Dongnai river system and offers a practical framework for hydrodynamic modeling in data-scarce~~regions and underscores the importance of incorporating discharge data~~ , ~~even if it has important uncertainties associated with it, for enhancing model accuracy. The model outputs have practical implications for water resource management and decision-making in this estuary system and all model output is provided in open-access format in Rodrigues Do Amaral et al. (2024)~~ 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~~ MAGE model boundary conditions

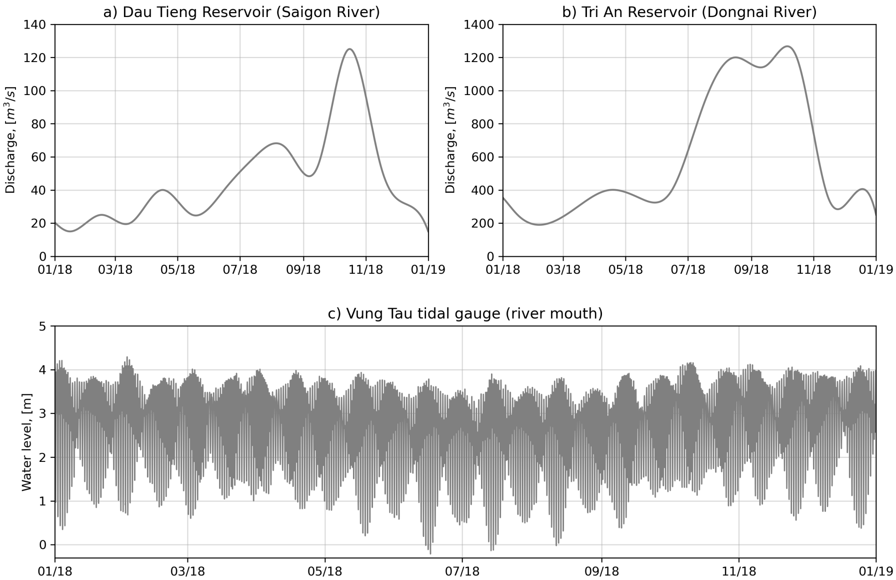

Figure A1. Boundary conditions used in ~~Mage~~ MAGE model: example for the year 2018. a) Upstream boundary condition for the Saigon river branch: discharge at the Dau Tieng reservoir. b) Upstream boundary condition for the Dongnai river: discharge at the Tri An reservoir. c) Downstream boundary condition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

Appendix B: Calibration results: rRMSE and R^2

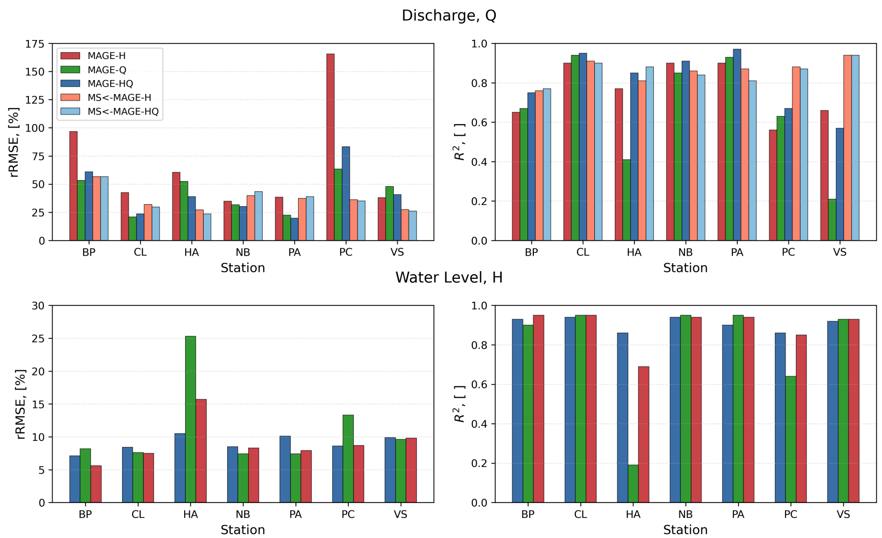

Figure B1. Calibration results for the ~~Mage~~ MAGE model and for the MS<-MAGE coupling. rRMSE and R^2 between model output and calibration data from the SIHYMECC measurement locations are shown. Dark red, green and dark blue bars represent the MAGE-H, MAGE-Q and MAGE-HQ results. Light red and light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

Appendix C: Validation results: R^2

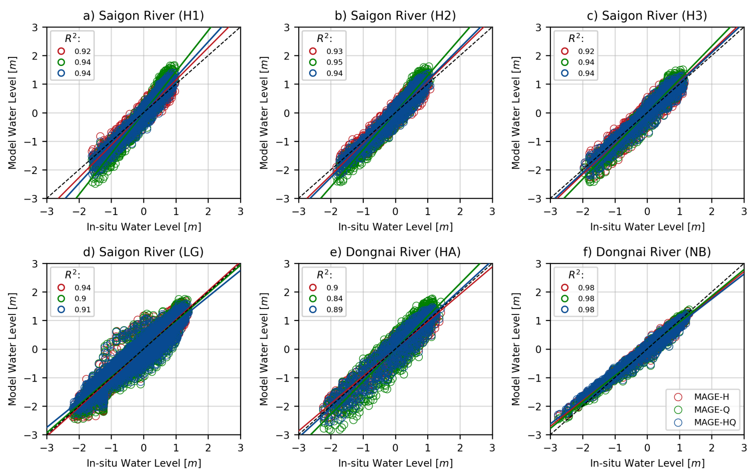

Figure C1. Linear regression lines and R^2 values between CARE water level measurements and model water level output. The black dashed line represents the $y = x$ line. Red, green and blue circles represent the MAGE-H, MAGE-Q and MAGE-HQ results. Solid lines represent linear regressions for each model 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.

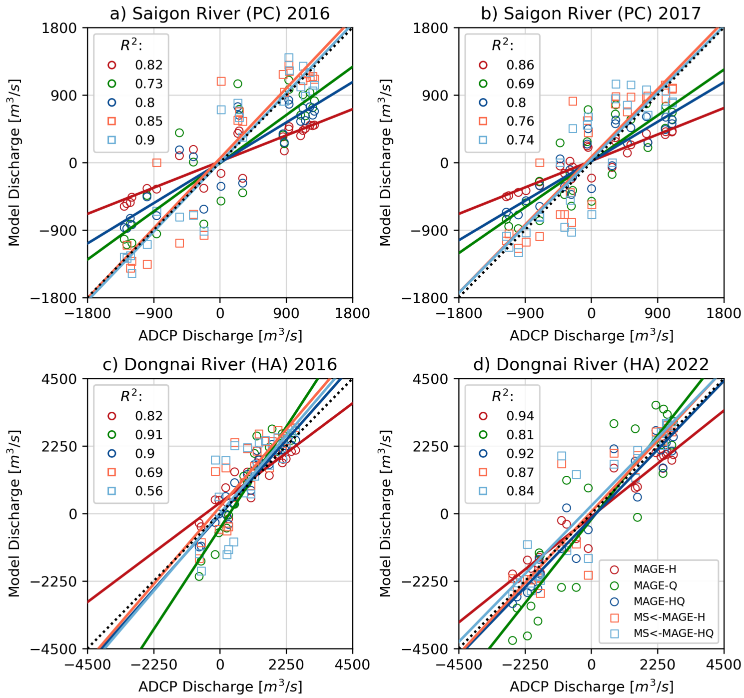

Figure C2. Linear regression lines and R^2 values between ADCP discharge and model discharge. The black dotted line represents the $y = x$ line. Red, green and blue circles represent the MAGE-H, MAGE-Q and MAGE-HQ results and blue and orange squares the MS<-MAGE-H and MS<-MAGE-HQ results. Solid lines 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.

References

Babut, M., Mourier, B., Desmet, M., Simonnet-Laprade, C., Labadie, P., Budzinski, H., De Alencastro, L. F., Tu, T. A., Strady, E., and Gratiot, N.: Where has the pollution gone? A survey of organic contaminants in Ho Chi Minh city / Saigon River (Vietnam) bed sediments, Chemosphere, 217, 261–269, https://doi.org/10.1016/j.chemosphere.2018.11.008, 2019.

Brent, R. P.: Algorithms for Minimization Without Derivatives, Courier Corporation, ISBN 978-0-48614368-2, https://books.google.nl/books/about/Algorithms_for_Minimization_Without_Deri.html?id=AITCAgAAQBAJ&redir_esc=y, 2013.

Caldwell, P. C., Merrifield, M. A., and Thompson, P. R.: Sea level measured by tide gauges from global oceans — the Joint Archive for Sea Level holdings (NCEI Accession 0019568), Dataset, Version 5.5, https://doi.org/10.7289/V5V40S7W, 2015.

Camenen, B., Dramais, G., Le Coz, J., Ho, T. D., Gratiot, N., and Piney, S.: Estimation d'une courbe de tarage hauteur-dénivelée-débit pour une rivière influencée par la marée, La Houille Blanche - Revue internationale de l'eau, 5, 16–21, https://doi.org/10.1051/lhb/2017039, 2017.

Camenen, B., Gratiot, N., Cohard, J.-A., Gard, F., Tran, V. Q., Nguyen, A.-T., Dramais, G., van Emmerik, T., and Némery, J.: Monitoring discharge in a tidal river using water level observations: Application to the Saigon River, Vietnam, Sci. Total Environ., 761, 143 195, https://doi.org/10.1016/j.scitotenv.2020.143195, 2021.

Camenen, B., Faure, J.-B., Décanis, S., and Dieval, L.: A 1D Numerical Tool for Real Time Modelling of a Complex River Network, in: Advances in Hydroinformatics, Proc. 6th SimHydro conference, Sophia-Antipolis, France, 2021, pp. 41–52, Springer, ISBN 978-981-19-1600-7, https://doi.org/10.1007/978-981-19-1600-7_3, 2022.

Camenen, B., Gerarduzzi, K., Terraz, T., Rodrigues do Amaral, F., Gratiot, N., and Pellarin, T.: 1D numerical modelling of a complex tidal river: case of the River Saigon, Vietnam, in: Proc. 7th SimHydro conference, Chatou, France, 2023.

Chen, Y.-C., Yang, T.-M., Hsu, N.-S., and Kuo, T.-M.: Real-time discharge measurement in tidal streams by an index velocity, Environ. Monit. Assess., 184, 6423–6436, https://doi.org/10.1007/s10661-011-2430-y, 2012.

Eltner, A., Sardemann, H., and Grundmann, J.: Technical Note: Flow velocity and discharge measurement in rivers using terrestrial and unmanned-aerial-vehicle imagery, Hydrol. Earth Syst. Sci., 24, 1429–1445, https://doi.org/10.5194/hess-24-1429-2020, 2020.

FranceInfo: Vietnam : la canicule provoque une grave sécheresse, FranceInfo, https://www.francetvinfo.fr/meteo/canicule/vietnam-la-canicule-provoque-une-grave-secheresse_6526445.html#at_medium=5&at_campaign_group=1&at_campaign=video&at_offre=3&at_variant=V3&at_send_date=20240505&at_recipient_id=726375-1571699586-49b9ee82, 2024.

Grund, F.: Forsythe, G. E. / Malcolm, M. A. / Moler, C. B., Computer Methods for Mathematical Computations. Englewood Cliffs, New Jersey 07632. Prentice Hall, Inc., 1977. XI, 259 S, Z. angew. Math. Mech., 59, 141–142, https://doi.org/10.1002/zamm.19790590235, 1979.

Heinrich, P., Hagemann, S., Weisse, R., Schrum, C., Daewel, U., and Gaslikova, L.: Compound flood events: analysing the joint occurrence of extreme river discharge events and storm surges in northern and central Europe, Nat. Hazards Earth Syst. Sci., 23, 1967–1985, https://doi.org/10.5194/nhess-23-1967-2023, 2023.

Launay, M., Dugué, V., Faure, J.-B., Coquery, M., Camenen, B., and Le Coz, J.: Numerical modelling of the suspended particulate matter dynamics in a regulated river network, Sci. Total Environ., 665, 591–605, https://doi.org/10.1016/j.scitotenv.2019.02.015, 2019.

Lossouarn, C., Quertamp, F., Gratiot, N., Fenghua, S., and Daigo, Y.: Water Megacities and Global Change: Portraits of 15 Emblematic Cities of the World, ISBN 978-92-3-100161-1, https://www.researchgate.net/publication/313376505_Water_Megacities_and_Global_Change_Portraits_of_15_Emblematic_Cities_of_the_World, 2016.

Mendez Rios, F., Le Coz, J., Renard, B., and Terraz, T.: Bayesian calibration of a 1D hydrodynamic model used as a rating curve in a tidal river: Application to the Lower Seine River, France, EGU General Assembly Conference Abstracts, pp. EGU–6587, https://doi.org/10.5194/egusphere-egu23-6587, 2023.

Ngo, M. T., Lee, J. M., Lee, H. A., and Woo, N. C.: The sustainability risk of Ho Chi Minh City, Vietnam, due to saltwater intrusion, Geosci. J., 19, 547–560, https://doi.org/10.1007/s12303-014-0052-4, 2015.

Nguyen, A. T., Némery, J., Gratiot, N., Garnier, J., Dao, T. S., Thieu, V., and Laruelle, G. G.: Biogeochemical functioning of an urbanized tropical estuary: Implementing the generic C-GEM (reactive transport) model, Sci. Total Environ., 784, 147 261, https://doi.org/10.1016/j.scitotenv.2021.147261, 2021.

Nguyen, A. T., Némery, J., Gratiot, N., Dao, T.-S., Le, T. T. M., Baduel, C., and Garnier, J.: Does eutrophication enhance greenhouse gas emissions in urbanized tropical estuaries?, Environ. Pollut., 303, 119 105, https://doi.org/10.1016/j.envpol.2022.119105, 2022.

Nguyen, P. T. B., Koedsin, W., McNeil, D., and Van, T. P. D.: Remote sensing techniques to predict salinity intrusion: application for a data-poor area of the coastal Mekong Delta, Vietnam, Int. J. Remote Sens., https://www.tandfonline.com/doi/abs/10.1080/01431161.2018.1466071, 2018.

Nguyen, T. T. N., Némery, J., Gratiot, N., Strady, E., Tran, V. Q., Nguyen, A. T., Aimé, J., and Peyne, A.: Nutrient dynamics and eutrophication assessment in the tropical river system of Saigon – Dongnai (southern Vietnam), Sci. Total Environ., 653, 370–383, https://doi.org/10.1016/j.scitotenv.2018.10.319, 2019.

Orie, A.: Hundreds of thousands of fish die off in Vietnam as heatwave roasts Southeast Asia, CNN, https://edition.cnn.com/2024/05/02/climate/mass-fish-die-off-vietnam-intl-scli/index.html, 2024.

Rodrigues do Amaral, F., Trung, T. N., Pellarin, T., and Gratiot, N.: Datasets of high-resolution water level and discharge from the Saigon-Dong Nai estuary system impacted by a developing megacity, Ho Chi Minh City - Vietnam, Data in Brief, 48, 109 147, https://doi.org/10.1016/j.dib.2023.109147, 2023.

Rodrigues Do Amaral, F., Camenen, B., Nguyen, T. T., Tran, A. T., Pellarin, T., and Gratiot, N.: Water discharge and water level output from the MAGE 1D hydrodynamic model for the Saigon and Dongnai rivers, Vietnam, 2016-2022, https://doi.org/10.23708/KLQMSR, 2024.

Rodrigues do Amaral, F., Pellarin, T., Tin, T. N., Tu, T. A., and Gratiot, N.: Enhancing discharge estimation from SWOT satellite data in a tropical tidal river environment, PLOS Water, 3, e0000 226, https://doi.org/10.1371/journal.pwat.0000226, 2024.

Rouby, P.-A., Camenen, B., Pénard, L., Kieffer, L., and Terraz, T.: Pamhyr2: A Graphical User Interface for 1D Hydro-Sedimentary Modelling of Rivers, in: Advances in Hydroinformatics—SimHydro 2023 Volume 2, pp. 485–497, Springer, Singapore, ISBN 978-981-97-4076-5, https://doi.org/10.1007/978-981-97-4076-5_33, 2024.

Ruhl, C. and Simpson, M.: Computation of discharge using the index-velocity method in tidally affected areas, Scientific Investigations Report, https://www.semanticscholar.org/paper/Computation-of-discharge-using-the-index-velocity-Ruhl-Simpson/033dd0d523f5bb811f60e0ff38675c7de1e0b02a, 2005.

Scheiber, L., Hoballah Jalloul, M., Jordan, C., Visscher, J., Nguyen, H. Q., and Schlurmann, T.: The potential of open-access data for flood estimations: uncovering inundation hotspots in Ho Chi Minh City, Vietnam, through a normalized flood severity index, Nat. Hazards Earth Syst. Sci., 23, 2313–2332, https://doi.org/10.5194/nhess-23-2313-2023, 2023.

Souhar, O. and Faure, J.-B. FaureJ.-B.: Approach for uncertainty propagation and design in Saint Venant equations via automatic sensitive derivatives applied to Saar river, Can. J. Civ. Eng., https://doi.org/10.1139/L09-057, 2009.

Vachaud, G., Quertamp, F., Phan, T. S. H., Tran Ngoc, T. D., Nguyen, T., Luu, X. L., Nguyen, A. T., and Gratiot, N.: Flood-related risks in Ho Chi Minh City and ways of mitigation, J. Hydrol., 573, 1021–1027, https://doi.org/10.1016/j.jhydrol.2018.02.044, 2019.

van Emmerik, T., Strady, E., Kieu-Le, T.-C., Nguyen, L., and Gratiot, N.: Seasonality of riverine macroplastic transport, Sci. Rep., 9, 1–9, https://doi.org/10.1038/s41598-019-50096-1, 2019.

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson, J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., Carey, C. J., Polat, İ., Feng, Y., Moore, E. W., VanderPlas, J., Laxalde, D., Perktold, J., Cimrman, R., Henriksen, I., Quintero, E. A., Harris, C. R., Archibald, A. M., Ribeiro, A. H., Pedregosa, F., van Mulbregt, P., and SciPy 1.0 Contributors: SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python, Nature Methods, 17, 261–272, https://doi.org/10.1038/s41592-019-0686-2, 2020.

Wood, M., Haigh, I. D., Le, Q. Q., Nguyen, H. N., Tran, H. B., Darby, S. E., Marsh, R., Skliris, N., Hirschi, J. J.-M., Nicholls, R. J., and Bloemendaal, N.: Climate-induced storminess forces major increases in future storm surge hazard in the South China Sea region, Nat. Hazards Earth Syst. Sci., 23, 2475–2504, https://doi.org/10.5194/nhess-23-2475-2023, 2023.

Xu, H., Tian, Z., Sun, L., Ye, Q., Ragno, E., Bricker, J., Mao, G., Tan, J., Wang, J., Ke, Q., Wang, S., and Toumi, R.: Compound flood impact of water level and rainfall during tropical cyclone periods in a coastal city: the case of Shanghai, Nat. Hazards Earth Syst. Sci., 22, 2347–2358, https://doi.org/10.5194/nhess-22-2347-2022, 2022.

Zakharova, E., Nielsen, K., Kamenev, G., and Kouraev, A.: River discharge estimation from radar altimetry: Assessment of satellite performance, river scales and methods, J. Hydrol., 583, 124 561, https://doi.org/10.1016/j.jhydrol.2020.124561, 2020.