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Calibration Approaches for Hydraulic River Models for High and Low Flows: A Review

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Abstract

Global climate change affects all aspects of river processes. It is expected that discharge extremes will occur more often in the future and that the probability of high and low flows in a shorter period will increase. Given these changes in hydrometeorological conditions, the question arises whether it is possible to set up a hydraulic model that simulates both high, intermediate and low flows in rivers accurately. However, hydraulic models are currently calibrated for a specific discharge range. Consequently, it is not possible to evaluate the effects of river interventions for a wide range of conditions with such a calibrated model. Therefore, this study gives an overview of the current state of hydraulic calibration approaches applied in literature and aims to give insights in how these calibration approaches can be improved such that a hydraulic model can be calibrated and applied for varying discharge conditions. Exploring the literature showed that the most commonly used parameter for calibration is roughness that is calibrated one time for one specific discharge or calibrated separately for different calibrated ranges.

Keywords: Hydraulic river modelling; High flow; Low flow; Calibration; Roughness

1. INTRODUCTION

Global climate change affects all aspects of river processes, such as the discharge and sediment supply (Ashmore and Church, 2000; Palmer et al., 2008). Hydrological studies on rivers in Central and Eastern Europe show that both high flows and low flows will occur more pronounced and frequently in the future (Klijn et al., 2018; Piniewski et al., 2017; Svensson et al., 2005). High discharges in the winter are expected to become more severe, whereas low flows will occur over a more extended period in the summer. For instance, according to Demirel et al. (2013), climate change will impact the seasonality of low flows in the Rhine river in the Netherlands. The timing of low flows will be different in the future, with more frequent low flows in the summer instead of the winter.

In hydraulic studies, high and low flows are generally modelled using separately calibrated models. More specifically, models are mainly developed for high flow conditions because a flood directly affects humans' lives, and flood safety has been a fundamental issue for centuries. However, low flow conditions are also important for several river functions like navigation, irrigation, drinking water supply and cooling water supply. Calibrating a hydraulic model such that it can simulate an entire hydrograph continuously with acceptable accuracy has the potential to be used to evaluate the effects of river interventions on both high and low flow conditions in the future.

Environmental models typically generate an approximate description of a system. Natural systems like rivers are usually sophisticated and complex, and hydraulic models cannot consider all details of a natural system with reasonable computational time. As a result, there is always a difference between observed and simulated variables (Janssen and Heuberger, 1995). The differences between model results and observations occur because of errors in simulating the natural systems. Errors can be reduced by improving system knowledge and calibrating the model (Khanarmuei et al., 2019).

The first step to improve a hydraulic model is to identify the sources of errors. The sources of errors and uncertainties for a hydraulic model causing differences between observed and simulated variables are categorized into three groups. The first group is the uncertainty related to the numerical solution, the second one is related to the model structure such as model dimension and mesh resolution, and the third group is the quality of used data such as bathymetric data, boundary conditions data (water level or discharge data) and roughness values (Bessar et al., 2020, Pappenberger et al., 2005, Walker et al., 2003). Any change in these uncertain model factors could affect the model results. For example, Bomers et al. (2019) showed that any change in mesh shape and resolution affects the calibrated main channel roughness. The remaining errors after improving the system knowledge are compensated with calibration by adjusting a set of parameters. The parameters modified through the calibration process are commonly unidentified and cannot be imported from prior experiments because of different circumstances (Walker et al., 2003).

This study aims to understand currently applied calibration approaches for hydraulic river models and gives insight into the potential ways of improving these approaches such that they can be applied for varying discharge conditions. This article is organized as follows: In section 2 the existing calibration approaches are discussed. Section 3 discusses how the existing calibration approaches can be improved such that they can be applied for varying discharge conditions, and in section 4, the conclusions are summarised.

2. EXISTING CALIBRATION APPROACHES

As mentioned in section 1, calibration is essential in hydraulic modeling to ensure accurate model predictions. This section explores some of the hydraulic modeling studies with different calibration approaches (Table 1).

Table 1. Hydraulic modelling studies with calibration approach

Reference	Case study	D*	Software	Boundary condition for calibration			Calibration approach
				Time period	Discharge range	Event	
Horritt et al. 2002	River Severn, UK	1D and 2D	HEC RAS (1D), TELEMAC-2D and LISFLOOD-FP (2D)	4 days	high flow	1998 and 2000 events.	floodplain and channel friction (one value for each)
Pappenberger et al., 2005	River Morava, Czech Republic and River Severn, UK	1D	HEC-RAS	4 days	high flow	1998 flood	main channel roughness
Warmink et al. 2007	River Waal, the Netherlands	2D	WAQUA	1 day	low flow to high flow	flood events 1993 and 1995,	main channel roughness for eight different water levels
Chandranath et al. 2008	Elbe River, Germany	1D and 1D–2D	1D MIKE11 and 1D–2D MIKEFLOOD	around 60 days	moderate and high flows	four flood events	main channel and flood plain roughness
Lai 2010	Sandy River Delta , Troutdale, US	2D	numerical code, SRH-2D	3 days		October 2005	main channel and floodplain roughness calibration
Paarlberg et al. 2012	River Waal, the Netherlands	1D	SOBEK		low to high flow	1995 discharge wave	main channel roughness coefficient as a function of the river discharge
Gharbi et al. 2016	Medjerda River, Tunisia	1D and 2D	HEC RAS (1D) and MIKE 11 (1D), TELEMAC (2D)	around 30 days		flood event in January 2003	overall roughness calibration
Xu et al., 2017	Yangtze River, China	1D	numerical code of Saint-Venant	12 days		Flood event 2009	overall roughness calibration for different ranges
Yossef et al., 2018	Meuse River, the Netherlands	2D	Delft3D Flexible Mesh suite		low to high flow	Steady discharges	calibration factor is multiplied by the roughness of main channel and floodplain for different discharge ranges.
Domhof et al., 2018	River Waal, the Netherlands	1D	SOBEK 3	4 days	low to high flow	1995 discharge wave	main channel roughness for different discharge range
Kuriqi and Ardiçlioğlu, 2018	Loire River, France	1D	HEC-RAS	3 days	high flow and low flow		main channel roughness for different discharge range
Bomers et al. 2019b	River Waal, the Netherlands	2D	Delft3D Flexible Mesh suite	3 days	high flow	1995 discharge wave	main channel roughness
Bomers et al. 2019a	upstream part of Rhine delta, the Netherlands and Germany	1D–2D	HEC-RAS		high flow	1995 discharge wave	main channel roughness

Bessar et al. 2020	Chaudière River, Canada	1D	HEC-RAS	around 10 days	low, moderate and high flows	discharge waves	channel roughness as a function of river flow

** D; Dimension.*

Hydraulic models are generally calibrated by changing the roughness parameter of the main channel and/ or floodplain. The roughness coefficient represents the flow resistance, including the bed's physical and flow conditions. However, the actual value of the roughness under different circumstances is generally unknown (Xu et al., 2017) and hence its value needs to be found through calibration . Another reason to calibrate the roughness is that the model results are very sensitive to the roughness. In the following the main calibration approaches used in the literature are discussed in two sections, section 2.1 is about one time roughness calibration approaches for high flow boundary conditions and section 2.2 roughness calibration for different discharge ranges.

2.1 One Time Roughness Calibration for A Specific Boundary Conditions

The most commonly applied approach to calibrate hydraulic models is to calibrate the main channel roughness for a specific discharge range (Bomers et al., 2019a, Bomers et al., 2019b, Gharbi et al., 2016, Horritt and Bates, 2002, Pappenberger et al., 2005, Lai, 2010). This calibration approach is based on changing the main channel roughness until simulated water levels are close to measured water levels. Bomers et al. (2019b) used the main channel roughness calibration approach to enable accurate simulation of the 1995 Rhine river flood event. Calibration was performed on the three days with the highest measured water levels during this flood event to reach a high accuracy in the simulated water level (the maximum difference between observed and simulated water level was 1 cm). This study showed that the calibrated roughness values are different for models with different mesh set-ups. Pappenberger et al. (2005) also used this calibration approach for an evaluation of the uncertainty of the roughness coefficients in hydraulic models. Roughness calibration was performed by trying different sets of randomly chosen Manning coefficients between 0.001 and 0.9. Two different rivers were used as case studies. The boundary conditions applied for the calibration were four days of maximum water levels of flood waves. The results indicate that the upstream boundary condition significantly affects the calibrated roughness values and presented the uncertainty in roughness coefficients. Model calibration for a specific high flow range will be accurate for this specific discharge range and less accurate when applied to lower or higher discharges. However, this generally is not a problem since most studies focus on flood inundation and flood safety, and the aim of these studies is not related to the accuracy of the model for low flows. The limitation of these models is that because the model errors are all compensated through the main channel roughness, sometimes the roughness values deviate from physically realistic values.

Calibrating one roughness coefficient for the whole channel (floodplain and main channel) could also be done when due to main purpose of the study, the highest accuracy of water level predicting is not required. For instance, Horritt et al. (2002) used one calibrated roughness value for the main channel and floodplain to investigate the effects of mesh resolution and topographic data quality on the prediction performance of a hydraulic model. The results showed that despite the errors caused by the roughness calibration, the sensitivity of the model results to mesh resolution and topographic data is low. Gharbi et al. (2016) also used one calibrated roughness coefficient for both floodplain and main channel to analyse the sediment transport during the floods. Gharbi et al. (2016) calibrated the model for an entire hydrograph. The calibrated roughness is relatively high The calibrated roughness is relatively high, and the result showed that the volume error is around 12%, but the error in the pick of flow is less than 2%.

Lai (2010) calibrated a numerical model for open channel flow by adjusting the main channel and floodplain roughness once and then used the calibrated roughness of main channel and floodplain to evaluate the applicability of arbitrarily shaped mesh cells to simulate open channel flow for subcritical, transcritical, and supercritical flows. In this study, the calibration was done based on comparing the simulated water level in the main channel with measurement, but the validation was based on comparing the predicted velocity with field data. The measured velocities had large fluctuations, but the model result generally agreed with the measurements.

2.2 Roughness Calibration for Different Discharge Ranges

In order to simulate a wider discharge range accurately, some studies calibrated the model for different discharge ranges separately (Bessar et al., 2020, Domhof et al., 2018, Kuriqi and Ardiçlioğlu, 2018, Paarlberg and Schielen, 2012, Warmink et al., 2007, Xu et al., 2017, Yossef et al., 2018, Chatterjee et al., 2008). There is no clear line between the calibration approach mentioned in section 2.1 and the calibration approaches that are done for different discharge ranges. Chandranath et al. (2008) evaluated a proposed flood emergency storage area using hydrodynamic modelling with one calibrated roughness for the main channel and one for the floodplain. Although they did not use different calibrated roughness values for different discharge ranges, the calibration was done in two stages. First, the roughness of the main channel is calibrated using a moderate discharge as boundary condition, and then by using the new calibrated main channel roughness and a higher discharge as boundary condition, the floodplain roughness is determined. This study used both 1D (MIKE11) and 1D–2D (MIKEFLOOD) models for modelling the river and the emergency storage. The 1D model showed more sensitivity to the main channel roughness value compared to the 1D–2D model.

Yossef et al. (2018) used roughness calibration approach to model the Rhine river branches in the Netherlands for five discharge levels from low to high flows. In this study, the physical roughness of the main channel and floodplain is multiplied by a calibration factor. The calibration data set for this model contains discharges as upstream boundary conditions and water levels as observations for the calibration. The calibration results include separate calibration factors for each discharge level. The validation results showed that the model works well for different discharge ranges. Kuriqi and Ardiçlioğlu (2018) investigated the hydraulic regime of the Loire river in France. Both a high flow data set of 2018 and low flow data sets of 2011 and 1012 were used for calibration, in which t Manning coefficient of the main channel was adapted for different discharges. The validation results showed that the model performs well for both data sets with a maximum difference of 15 cm between the observed and simulated water level. Domhof et al. (2018) calibrated the Manning coefficient of the main channel in a 1D hydrodynamic model of the Waal river to evaluate how the calibrated hydraulic roughness changes as a function of the discharge and location in the longitudinal direction of the river. The calibration was done for two different discharges of the flood event in 1995 for around four days. In the first pick, the water level is up to bankfull, and the second one is a flood stage. For the validation the water level is successfully predicted using the three months of discharge waves for 1993 and 2011. Since the results showed that the calibrated roughness is sensitive to the discharge, the calibration firstly was done for two discharge levels, one with a full main channel and one for high flow (flood), and then the model is calibrated for six discharge levels. The water level prediction improved by 9% by separately calibrating six discharge levels instead of two discharge levels. This study asserted that for the Waal river, the calibrated roughness is sensitive to the discharge mainly for two reasons: the first one is the human intervention, compartmentation of the floodplain of the Waal river and the second one is because of the growth of the river dunes. Because with an increase of the dune dimensions the physical roughness also increases and this leads to increasing water levels (Gensen et al., 2021). Warmink et al. (2007) calibrated the main channel roughness of the Waal river for eight different discharge levels. These eight boundary conditions used for calibration are 24 hours around the peaks of the flood waves in 1993 and 1995 with different magnitudes. The results showed that the calibrated roughness value for lower discharge is higher than the calibrated roughness value for high flows.

Bessar et al. (2020) developed an adaptive flow-based calibration for a 1D hydraulic model. In this calibration approach, a set of relationships describing the variation of roughness coefficients as a function of the flow for each river segment with observed water level data is determined from different flood events to calibrate one relation between roughness and flow for the main channel and floodplain. The calibration is done for four flood events with low, medium, and high magnitudes. The calibration results show that the model works well for high and medium discharges but does not provide accurate results for low flows. A possible explanation given by the authors is the availability of insufficient and inaccurate bathymetry data resulting in extremely low values for the calibrated roughness during low flows. The models are validated for two moderate and high flow events, and the results showed that the model performed well. Another example of using a flow-related roughness approach is presented by Xu et al. (2017), who developed a calibration approach for real-time flood forecasting by combining a hydraulic model and a data assimilation algorithm (the Bayesian particle filter approach). In this study, the roughness coefficient value is calibrated for each discharge range, and the data assimilation algorithm finds a non-linear stochastic relation? between the discharge and the roughness. The advantage of this approach is that the relation between roughness and discharge can be updated with any new boundary condition and observation data.

The most important conclusion from literature on roughness calibration for different discharge ranges is that the calibrated roughness is sensitive to the discharge. One of the reasons for this behavior is that the roughness represents the flow resistance including the flow conditions, such as the flow turbulence and dunes.

3. DISSCUSION

Calibration is one of the most important steps in developing a hydraulic model and includes the selection of calibration parameters and boundary conditions. The most commonly used parameter to calibrate hydraulic models is the roughness. Based on the purpose of the study, the calibrated roughness could be just the main channel roughness or both the main channel roughness and the flood plain roughness.

In this paper, two calibration approaches are discussed. The first calibration approach aims to find one single value for the roughness. In this approach, the boundary condition that is used for the calibration is the discharge range related to the purpose of the study. For example, a model used for flood safety assessment is calibrated for the highest discharge range. In these models, the accuracy of the simulation results decreases as the difference between the boundary condition used for calibration and the boundary condition used for validation increases. The second calibration approach is more discharge-related than the first approach. In this approach, the calibration process is repeated for different discharge ranges. Furthermore, the related roughness values are used for the validation and simulation. The results of these models have a higher accuracy for a broader range of discharges.

Based on the limitations of the literature, there are some potential ways to improve the existing calibration methods to get a calibration method that works for varying discharge conditions, such as calibrating only the main channel affects the discharge distribution between the main channel and floodplain. Therefore, calibrating both the main channel and floodplain with an equal calibrated factor for both could manage the discharge distribution. The other option to the result of a model is about the initial flood plain roughness; models in the Netherlands calibrated for winter conditions in which floodplain roughness is different from summer conditions and considering the seasonal roughness could make an improvement in simulation results.

The geometry is also one of the sources of errors and depends on the available topographic data and how this data is discretized by the mesh. Bathymetry calibration has been done for other water systems, and could be an option for river systems as well. In this regard Khanarmuei et al. (2019) found a difference in elevation between the bathymetry points gathered from a LIDAR survey and the ones manually measured in the field for a micro-tidal estuary in Queensland, Australia. Due to this errors in measurements, they calibrated a hydraulic model applying a range of offset values for the main channel bathymetry and a range of roughness coefficients. In the first calibration step, different offset values with a constant main channel roughness were tested to find the best offset value and in the second step of the calibration the roughness value (Manning coefficient) was varied within a realistic range for the main channel roughness (0.016 to 0.030). The results showed that with a constant value for the roughness, the bathymetry calibration improved the model performance significantly compared to the non-calibrated model (reducing the RMSE by about 20%) (Khanarmuei et al., 2019). Regardless, the bathymetry calibration could also be an additional option to roughness calibration that will be considered in the upcoming studies for developing a hydraulic model with one single calibration approach.

4. CONCLUSIONS

A hydraulic river model requires an appropriate calibration approach to simulate water levels under varying flow conditions with high accuracy by improving the understanding of the river system's physical processes during discharge ranges and calibrating the model with a suitable approach. there are two different calibration approaches, one time roughness calibration approaches for a specific boundary conditions and roughness calibration for different discharge ranges. Both approaches calibrated the roughness. Advantage of first approach is that the roughness values is constant for different discharge ranges and the advantage of the second approach is the simulation result are with high accuracy for different discharges, while the first group are accurate for a specific discharge. The model accuracy maybe be compromised if it calibrated on both high and low flows (compared to calibration on either), but it is still worth it because with one time calibration for different discharges it is possible to simulate the whole hydrograph and the effect of preceding discharge events is considered for the next event in long-term simulations. Furthermore, with the help of such model, there will be room for future research to consider the effects of new interventions to mitigate both high and low flow conditions.

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