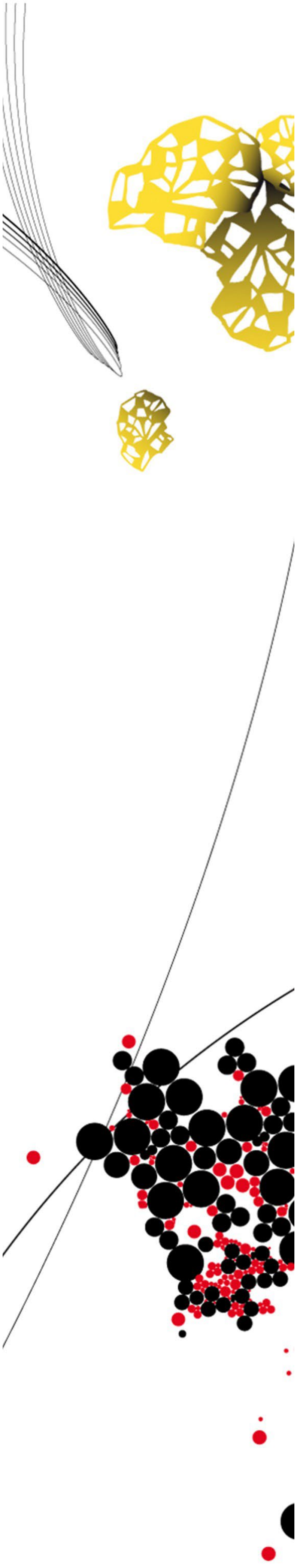

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Hydraulic river modelling approaches to link high flow and low flow conditions

Literature report

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HYDRAULIC RIVER MODELLING APPROACHES TO LINK HIGH FLOW AND LOW FLOW CONDITIONS

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November 2022

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Contents

1 Introduction

River management is often reminded of pretending the risks of river flood events. Nonetheless, low water is also considered a critical risk as many communities rely on the availability of a fresh water from the rivers for various purposes such as navigation, drinking water supply, nature development, and recreation. Therefore, in addition to periods of high flow, periods of low flow should also be considered in water management.

On the other hand, high and low flow periods have been paid more attention recently due to the effects of global climate change. Global climate change affects all aspects of river flow processes, and it is expected that river discharge extremes will occur more often in the future. High discharges in the winter are expected to become more severe, whereas low flows will occur over a more extended period in the summer.

An accurate prediction of river water levels is essential for adequate river management and fulfilling various purposes. Until now, high flows and low flows have been simulated using separate hydraulic models. However, due to climate change and the expected increase in the frequency of discharge extremes in a shorter period (for example, in one year), the question arises to what extent it is possible to simulate high and low flows in one model continuously. The advantage of such a model is that it enables the simulation of the entire hydrograph. The model then captures the effect of the preceding discharge conditions, such as the effects of varying river dune dimensions, on the water levels in upcoming conditions. The operation of a dam is an excellent example of the benefit of continuously modelling periods of high and low water to ensure a balanced water supply to meet the demand.

The aim of this literature review report is to introduce the objectives, structure and major issues involved in developing a hydraulic model for simulating different water levels continuously and gives an overview of the current state of the knowledge of river hydraulic modelling with a focus on the mesh set-up and calibration approach.

1.1 Objective and literature questions

This literature review gives an overview of the current understanding of river hydraulic modelling to develop a calibration approach for a hydraulic river model to accurately simulate water levels under varying flow conditions to enable evaluation of the effects of river interventions in high flow and low flow situations. The following questions are defined for this literature review:

1. What are the main steps for developing a hydraulic model?
2. What are the critical elements of a mesh in a hydraulic model?
3. What calibration methods exist in the literature for different flow ranges?
5. What is the influence of river interventions on the extreme high and low discharges?

This literature review focusses on hydraulic modelling of river systems in lowlands.

1.2 Outline

Section 1 of the literature review report introduce the objectives, structure and major issues involved in developing a model for different water levels. Section 2 discusses the first literature question about the main steps for developing a hydraulic models. Mesh set-up and calibration process are two of more important step of hydraulic modellings that are presents the question 2 and 3 in section 3 and 4, respectively. section 5 presents the current literature for intervention evaluation through the literature. the last chapter, presents some significant conclusion relating to main goal of the project.

2 Developing a hydraulic river model

This chapter answers the first question of this literature study: What are the main steps in developing a hydraulic model?

Hydraulic simulation of the river flow using software that implements the shallow water equations is a common way to model the river for investigating the water depth and calculating the water level. These aspects should be set based on each river's function and the corresponding management priorities. Yossef et al. (2018) established some essential design criteria for a hydraulic model based on the workshops with hydraulic modelling expertise. The established design criteria are model dimensions, mesh coverage and its resolution, timeframe of the expected simulations (from short-term to long-term), boundary conditions and forcing type, calibration and validation acceptance criteria, and desired computational time (Yossef et al., 2018). Considering the design criteria mentioned above the following four main aspects are defined for a hydraulic river model: model set-up, numerical or analytical approach, calibration and validation, (figure 1).

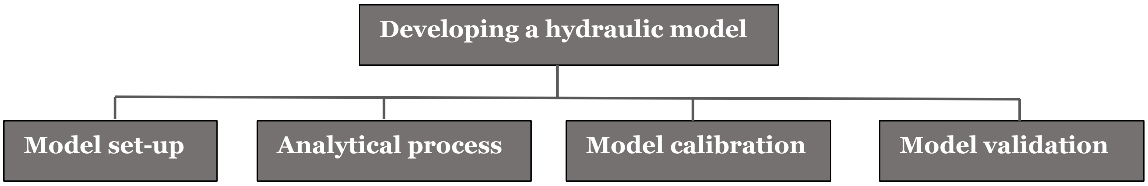


Figure 1, steps of developing a hydraulic river model

In modelling a river using a hydraulic software, the most effort takes place in model set-up and calibration process. The differences in the model structures in the representation of the flow geometry, the underlying equations and the numerical discretization as well as the model parameterization lead to different results. It means there are different predicted water levels for different discharges from low to high flow. The following sections will briefly discuss different aspects of developing a hydraulic model. Dimension, and schematization data are discussed under model set-up section 2.1, numerical or analytical processes are discussed in section 2.2. Mesh set-up that is a part of model set-up and hydraulic model calibration are discussed in separate chapters in more details due to their importance for this research and model validation as the last step of hydraulic modelling simulation is discussed briefly in section 2.3.

2.1 Model set-up

The model set-up has three steps: the dimension, the mesh set-up and the Schematization data, figure 2.

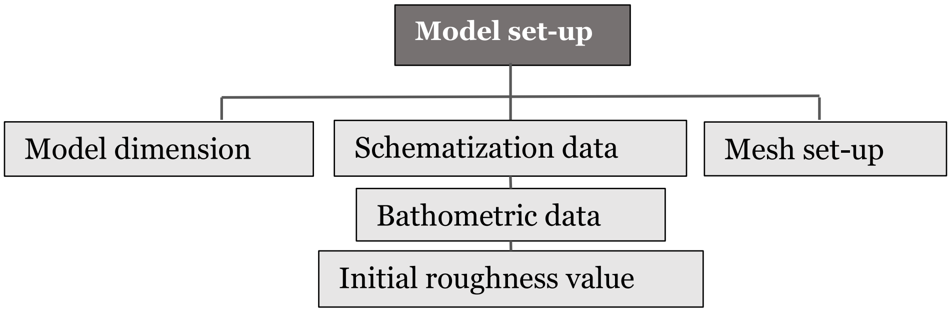
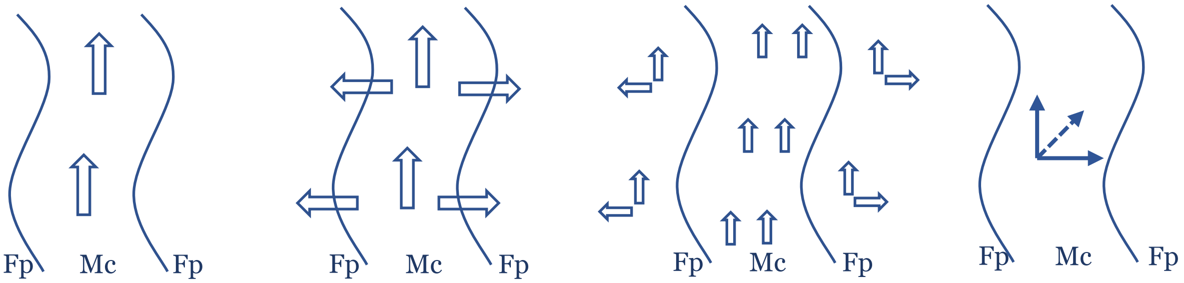


Figure 2, Model set-up steps

2.1.1 Dimension

Hydraulic models can be categorized based on their dimensions. In one dimensional (1D) models, flow is considered to move in both channel and floodplain in one direction along the river, (figure 3. a). In two dimensional depth-averaged (2D) models, flow is considered to move in two directions in both channel and floodplain (figure 3. b). It is also possible to combine a one-dimensional model with a two-dimensional model, as 1D in the main channel and 2D in the floodplain (figure 3. c), and in three dimensional (3D), flow is considered to move in three special dimensions (figure 3. d).



a) 1D *b) 2D* *c)1D-2D* *d)3D*

Figure 3, Different dimension set-up for hydraulic models, the arrows shows the direction simulated flow for floodplain (Fp) and main channel (Mc) (based on (Ye and McCorquodale, 1997))

The dimension of hydraulic models depends on the purpose of the model and the required dimension for solving the equations that are used for the model (Liu et al., 2019). Most traditional hydraulic modelling studies have used one-dimensional (1D) flow models. 1D models are still used for specific aims, such as long reaches or in cases where the vertical acceleration is negligible because the water depth is shallow relative to the width (Pappenberger et al., 2005) or for early warning systems in operational systems (Yossef et al., 2018). 1D models bathymetry is created using discrete cross-sections and considers only the longitudinally movement of water in line with the river direction (Liu et al., 2019). Compared to 1D models, 2D models consider two directions for water movement (longitudinal and lateral). 2D models present more detailed and accurate simulations of water levels and flood patterns (Bomers et al., 2019b). They are used for different purposes like flood safety, water quality, infrastructure development, etc. (Yossef et al., 2018). The bathymetry in 2D models is described with a continuous mesh covering the main channel and floodplain (Liu et al., 2019). 1D-2D combined models are usually used to discretize the main channel with a 1D mesh and the floodplain with a 2D mesh (Finaud-Guyot et al., 2011). They can also be used when some part of the domain has complex hydrodynamic conditions to be captured. Bomers et, al. (2019b) used a 1D mesh for the main channel and floodplain combined with a 2D mesh for the embanked areas. 3D models consider the vertical movement as an additional movement compare to 2D models. 3D models are used for detailed studies around structures (Yossef et al., 2018), and they are not feasible for long reaches because of their long computation times.

2.1.2 Schematization data

Schematization data is part of the required data for an appropriate hydraulic modelling that involve the bathymetric data, and initial roughness values. Meaningful hydraulic analysis and modelling of the river flow significantly relies on the quality of the input data (bathymetry and roughness values). Bathymetry measurements are the river bed elevation of the main channel, the floodplains, and the river's longitudinal profile (Verhoeven et al., 2003). The geometry of the river that is represented based on the bathymetry data is a source of uncertainty in hydraulic models (Pappenberger et al., 2005). Geometry data is considered a source of error from two points of view; the first is about the errors in measurements, and the next is since bed elevation data gathering is not a continuous process, the topographical measurements are just available every few years, while the model needs to be run for a specific event that happened in another time.

2.2 Analytical process

The theoretical hydraulic basis for large scale water surface profile calculation depends on the model's dimension (one-dimension or two-dimension) and the flow type (steady or unsteady). For 1D models, the water level for a steady flow is calculated for sequent cross-section by solving the Energy equations in an iterative process. The flow velocity in each cross-section is calculated based on the Manning equation. for 1D unsteady flow, water level calculation, the physical laws used are the principle of conservation of mass (continuity) and the principle of conservation of momentum (Brunner, 1995).

The 2D depth-averaged, unsteady hydraulic models are solved using the Navier-Stokes equations. Navier-Stokes equations describe the motion of the fluids in three dimensions, but in the case of the flow in the open channels, it is possible to consider some simplifications. Shallow water equations are the simplified version of Navier-Stokes equations by considering the following assumptions: incompressible flow, uniform density, hydrostatic pressure, using eddy viscosity for turbulent motion, and the last one is that the vertical length scale is much smaller than the horizontal length scale in open channels like rivers (Sadourny, 1975). The parameters that are involved in these equations are water depth, distance along the river, bottom slope, friction factor, gravitational acceleration, wetted perimeter, discharge, flow area, width at the water surface (the equations mentioned in this section are in the appendix). The friction factor used in the equations is one of the most arguable parameters because the exact value is hard to determine.

Friction in rivers is affected by many parameters such as river bed roughness, the shape of the cross-section, vegetation, obstacles, meanders, velocity distribution, etc. As a result, the value of the friction coefficient varies in space and time. Although many attempts have been made to calculate the coefficient's value theoretically, it seems that determining it from measurements can provide appropriate information on the values to be used for modelling (Verhoeven et al., 2003).

2.3 Validation

Model validation is assurance that a model has an adequate degree of accuracy within its range of applicability (Refsgaard and Henriksen, 2004). In another words validation is the comparison of the model output to an independent set of measurement data (not identical to the calibration data) to determine whether the model can reproduce the event with the required accuracy (Scholten et al., 2000).

3 Mesh set-up

Previous investigations have demonstrated that the mesh structure significantly affects the accuracy of outputs of shallow water equation models (Bilgili 2020). The impact of the effects of mesh structure on the outputs differ from low to high discharges; due to this issue mesh set-up is discussed in more detail.

Two-dimensional horizontal (2DH) models required a mesh to discretize the model domain. Each mesh has two aspects:

1. Mesh cell's shape:
    - curvilinear/structured
    - triangular/unstructured
2. Mesh size or mesh resolution

3.1 Mesh cell's shape

The mesh cell's shape is about the structure of cells stuck together to cover the whole domain of the river model. Cell shape and mesh structure are the modellers choices based on the priorities or software restrictions (Caviedes-Voullième et al., 2012). The first important criterion for mesh structure is that the mesh should be in line with the river main channel direction (Yossef et al., 2018).
As mentioned before, there are two different mesh cell shapes, structured (figure 4.) and unstructured (figure 5.). In the following, their advantages and disadvantages are discussed. Advantages of curvilinear, structured, or quadrangular cells are:

- The mesh is in line with the river's main channel direction, leading to efficient flow modelling and less numerical diffusion, especially in low flows (Bomers et al., 2019b).
- Quadrangles in structured meshes have a better convergence, and as a result, fewer cells are needed to cover the whole domain (Yossef et al., 2018).
- The time step could be relatively larger because of the larger volume of quadrilateral cells over triangle cells.

Furthermore, the disadvantages of the structured mesh cells are:

- An unnecessary high resolution happens in sharp inner bends in curvilinear meshes, which increases the computation time of the model.
- In curvilinear grid cells, the resolution of the floodplain is based on the resolution of the curvilinear grid cells in the main channel, and it is impossible to refine it (Bomers et al., 2019b).
- As the curvilinear cells are not flexible, it is impossible to represent the domain's natural geometric features.

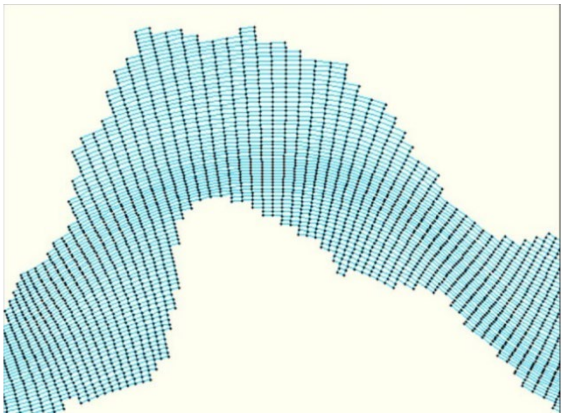


Figure 4, curvilinear, structured, or quadrangular cells mesh set-up (Bomers et al., 2019)

On the other hand, the unstructured meshes also have some advantages and disadvantages; the advantages are:

- Triangular grids are more flexible in shape and could represent different geometric features.
- The resolution of the unstructured mesh could also change locally if the region is sensitive (Hardy et al., 1999).

Moreover, the disadvantage is that the triangular mesh cells are not in the flow direction compared to structured meshes, leading to less accurate model output. It is also possible to apply hybrid meshes to use the advantages of different mesh cells (figure 6.). Bomers et al. (2019, b) showed that combining the two grid types with curvilinear mesh cells in the main channel and triangles in the floodplains for hydraulic 2DH modelling is a viable option.

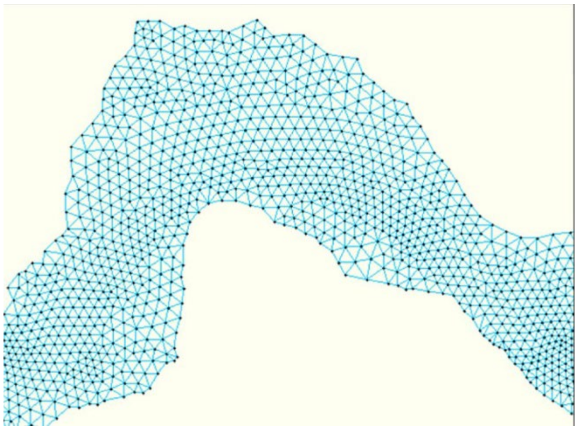


Figure 5, unstructured mesh set-up (Bomers et al., 2019)

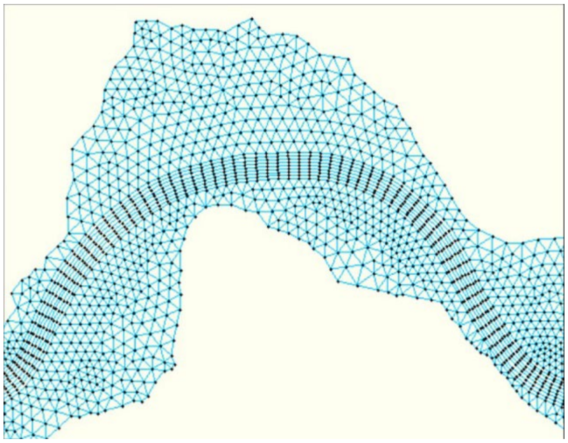


Figure 6, hybrid mesh set-up (Bomers et al., 2019)

3.2 Mesh resolution

The resolution of the mesh to discretize the geometry is commensurate with the input data describing the topography properties of the river and available computing power (Gustard and Demuth, 2009) and, in some cases, the stability of the model (Gharbi et al., 2016). Cell size and, in consequence, mesh resolution is not bordered by physical ranges (Hardy et al., 1999). A high mesh resolution is optimistic in terms of accuracy, but these models has a high computational time due to the more significant number of grid cells (Bomers et al., 2019b), while a coarser mesh with larger cells than the available data resolution can be appropriately selected to obtain satisfactory results without high computational cost by selecting an appropriate cell size (Caviedes-Voullième et al., 2012). Mesh resolution affects river bathymetry discretization, discharge capacity, and, consequently, water levels. Mesh with low-resolution results in lower depth-averaged flow velocities and, subsequently, higher water depths than the higher resolution and the measurements. This error is more pronounced for higher discharges (Bilgili 2020). As a result selecting a suitable mesh resolution is important because the hydraulic model results are sensitive to mesh resolution and on the other hand the computation times are also important due to the desired time and cost. (Hardy et al., 1999).

3.3 Overview of mesh in literature

Any change in two aspects (mesh cell's shape and mesh resolution) will alter the mesh set-up and affect the simulation results, and selecting a suitable mesh is an important step through simulating water level using hydraulic modellings (Hardy et al., 1999). In table 1, the shape and the resolution of the hydraulic models that are used in research are examined. Based on this table, it seems that although the shape of the mesh affects the model's result, it is more up to the researcher and the obligations of the used software. On the other hand, the model results are sensitive to the mesh resolution. After any change to the mesh set-up due to high or low flow situations or a mesh refinement to add river interventions such as a side channel, a new calibration is needed.

Table 1: overview of cell shape and resolution of meshes used in the literature

	Case study	Shape	Mesh Size, main channel	Mesh Size, Floodplain
(Yossef et al., 2018)	the Meuse River	quadrangular cells	at least 8 cells of at most 20 m wide	at most 40 m
(Berends et al., 2019)	the Waal River	unstructured numerical grid	40m by 15m	a maximum of about 120m by 120m
(Gharbi et al., 2016)	the Medjerda River	unstructured	5 m	about 50 m
(Alipour et al., 2021)	the Tovdal river	unstructured	15-20-25 m	150-200-250 m
(Horritt and Bates, 2002)	the Severn river	unstructured, triangular	3 cells in width (20-50 m)	about 30 -50m
(Horritt et al., 2006)	the Thames river	unstructured, triangular	10, 20 and 50 m	

(Warmink et al., 2007)	the Waal River	curvilinear	approximately 40 m	
(Le et al., 2020)	the Waal River	curvilinear	40 × 20 m	40 × 40 m
(Warmink et al., 2011)	the rivers Rhine and Meuse	curvilinear	approximately 40 m	
(Warmink et al., 2013)	the Waal River	curvilinear	approximately 40 m	
(Bomers et al., 2019b)	the Rhine river	hybrid grid	curvilinear	unstructured, triangular
(Booij, 2020)	the Ayeyarwady River	hybrid grid	25 ×25 m	
(Berends et al., 2021)	the Waal River	curvilinear	20 by 40 m	40 by 50 m

4 Calibration and Validation

Calibration in general means obtaining a certain degree of similarity and correspondence between the simulation results and observations by systematically changing uncertain factors or parameters (Klemeš 1986). In hydraulic models model calibration also means minimizing the error between simulated and observed water levels by modifying model parameters (Domhof et al. 2018). Calibration is about applying a boundary condition an selecting a parameter to calibrate for that specific boundary condition.

4.1 Boundary condition

The quality of the model calibration depends on the quality of data in the the hydraulic measurements. Hydraulic measurements are used to define the hydraulic characteristics of the model by providing discharges or water levels data as a function of time on the boundary conditions (Verhoeven et al. 2003). In low flows, the measurements should be both accurate and precise; but, the accuracy and precision at high flows may be of secondary importance (Gustard and Demuth 2009). The upstream boundary condition is usually a discharge time series in the river. There are several ways to analyse the time series of discharge to describe different discharge levels, from low to high flows. For example, low flow could be defined as an annual or a return period minimum (Brenk et al. 2021), a threshold discharge or based on the frequency of periods in which the discharge exceeded or the average of a period with the lowest water level in the river. Three statistics mostly used in water resource planning for low flows are mean flow (average discharge in a specific period, like a year), 95 percentile flow (the flow exceeded 95% of the time) and mean annual minimum (the minimum discharge of a specific period) (Gustard and Demuth 2009).

4.2 Calibration approach

The parameters modified through the calibration process are commonly the uncertain and important parameters that the model output is sensitive to. Pappenberger et al. announced the most important source of uncertainty for 1D flood inundation models as structure, implementation of the numerical scheme, topography, model input, and parameters (Pappenberger et al. 2005). In other words, the sources of errors and uncertainties are categorized into two groups, the first group is the model structure such as model dimension and mesh resolution, and the second group is the quality of used data such as topographic and bathymetric data, boundary conditions data (water level or flow data) and the roughness (Bessar, Matte, and Anctil 2020).

Previous studies show that the calibrated roughness is mainly sensitive to the discharge. However, most studies for accurate water level predictions calibrated the model for different discharge levels separately (Domhof et al. 2018). The roughness coefficient represents the resistance to the flow. There are some papers in which different parameters are calibrated. For example, Khanarmuei et al. (2019) calibrated a micro-tidal estuary hydraulic model applying a range of constant offset factors for bathymetry and a range of roughness coefficients. However, calibrating the roughness parameter is the most used calibration method for hydraulic models (Khanarmuei et al., 2019). In the calibration approach with the roughness as the calibration parameter, the newly calibrated roughness has no physical meaning anymore because it has been changed to reproduce the water levels at measurement stations. In other words, the main channel roughness is altered to compensate for errors in the model set-up. One of the commonly used ways to calibrate hydraulic models is to calibrate the main channel roughness and apply physical roughness values to the floodplains (Bomers et al., 2019b, Domhof et al., 2018). The calibration data set for this model contains discharges as forcing and water levels as observations in a limited time window. The calibration result includes separate calibration factors for each discharge level (Yossef et al., 2018). As calibrated roughness varies with the discharge, some studies have developed flow-based calibration methods (Xu et al., 2017). Bessar et al. (2020) presented a flow-based calibration method to model 1D flood events using a roughness factor adapted from relationships between roughness and flow for every segment and discharge range. All hydraulic modelling studies calibrated the models for a specific flow range. Most of them focused on high flows (Bessar et al., 2020, Xu et al., 2017), and some considered several flow ranges from high to low flows with separate calibration for each of them and the calibration result includes separate calibration factors for each discharge level (Kuriqi and Ardiçlioğlu, 2018, Yossef et al., 2018).

4.2.1 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 (Bilgili, 2020, Bomers et al., 2019a, Gharbi et al., 2016, Horritt and Bates, 2002, Lai, 2010, Pappenberger et al., 2005). 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 maximum 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 as an roughness calibration approach. 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 analyze the sediment transport during the floods and calibrated the model for an entire hydrograph. The calibrated roughness is relatively high, and the result showed that the volume error is around 12%, but the error in the peak 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.

4.2.2 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, Chatterjee et al., 2008, Domhof et al., 2018, Kuriqi and Ardiçlioğlu, 2018, Paarlberg and Schielen, 2012, Warmink et al., 2007, Xu et al., 2017, Yossef et al., 2018). 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 (Chatterjee et al., 2008).

Yossef et al. (2018) used a 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 2012 were used for calibration, in which the 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., 2020). 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.

A calibration process reduces systematic model errors (Khanarmuei et al., 2019). However, systematic errors can also be reduced by improving the physical characteristics of the model. For example, vegetation dynamics are usually neglected in hydraulic models. Booij (2020) developed a method to include the seasonal vegetation dynamics in space and time on migrating mid-channel bars of braided rivers in numerical morphodynamic model (Booij, 2020). Another example of improving the physics of the model is considering the dynamics of dunes in the roughness calibration process, as Paarlberg and Schielen (2012) did for a 1D Sobek model of a short section of the Waal river (Paarlberg and Schielen, 2012).

5 Interventions

An accurate and reliable water level simulation helps to adequately plan new interventions or evaluate interventions for different purposes (Bessar et al., 2020). Human intervention in river systems, especially for Dutch rivers, has been a familiar topic for centuries. River interventions and infrastructures are built to serve different functions and, focusing on individual functions may lead to conflicts with other functions (Havinga, 2020). One of the most important functions of interventions in the Netherlands is reducing flood levels such as in the ‘Room for the River’ program that started at the end of the 20th century (Klijn et al., 2018, Rijke et al., 2012). Berends et al. (2018) quantified the uncertainty of flood mitigation measures for the Waal river. The results show that any uncertainty of predicted flood mitigation could result in different design choices (Berends et al., 2019), which is valuable information for decision makers and modellers.

Most interventions aim to reduce the flood level by increasing the discharge capacity or preventing erosion of the main channel. These interventions are usually designed for flood events corresponding to a specific return period or discharge range. In the Netherlands, integrated water resource management considers other functions besides flood safety, such as the transport capacity for navigation, water security, and healthy ecosystems (Rijke et al., 2012). Therefore, it is important to know the effect of river interventions specifically designed for high flows on water levels during low flows and vice versa.

6 Conclusion

The purpose of this literature review report was to provide an overview of the current state of knowledge regarding river hydraulic modeling with a focus on the mesh set-up and calibration approach. The outcomes of this literature review could be summarized in four phases as below.

Mesh set-up can affect the simulation results significantly, and selecting a suitable mesh is as important as applying an appropriate calibration method (Hardy et al., 1999). By applying any change to the mesh set-up due to high or low flow situations or a mesh refinement to add river interventions such as a side channel, a new calibration is needed. With developing a mesh with the same discharge capacity as the real cross-section, there is no need to recalibrate the model after any change in model setup as long as the discharge capacity remains equal to the river cross sections. For an integrated model with the purpose of evaluating effects of interventions, the first challenge is developing a method that enables to setting up a mesh such that the discharge capacity is independent of the mesh resolution.

Hydraulic models used in literature are calibrated applying existing methods such as calibration of the main channel roughness or using a multiplication factor for the physical roughness on a specific discharge range, which is then validated for the same range. Hence, the performance of a model calibrated for a specific discharge range for other ranges is unknown. Studying the performance of a model for a different discharge range than the range used for calibration could identify which calibration method provides the most reliable results for which discharge range.

In the literature, no integrated model exists that is calibrated for different flow ranges. An integrated model considers the effect of past events in new situations resulting from continuously modelling varying discharge conditions. Enhancing the existing calibration method to develop one integrated model that accurately simulates various discharge ranges by determining physical model parameters, such as considering a varying roughness description since river dune dimensions change under varying discharges and the seasonal roughness of floodplains is important for high flows when floodplains are inundated.

Based on the literature, the effect of an intervention is evaluated using separate models for high and low flow situations by considering one single situation. However, an integrated model continuously simulates both situations and evaluates the effects of interventions in a specific discharge event, considering the effects of earlier boundary conditions.

Appendices

Steady flow

continuity equation:

Q = A . U

And motion by the equation of Bresse (Sturm, 2001,):

$$\frac{dh}{dx} = \frac{S_0 - \frac{f}{8g}\frac{PQ^2}{A^3}}{\sqrt{1 - S_0{}^2} - \frac{BQ^2}{gA^3}}$$

Where: h = water depth; x = distance along the river; S_0 = bottom slope; f = friction factor; g = gravitational acceleration; P = wetted perimeter; Q = discharge; A = flow area; B = width at the water surface.

The effect of all approximations made is concentrated in the friction factor, mainly taken from formula such as Manning-Strickler, Bazin, White-Colebrook-Thijsse. The quality of the numerical solution of this relatively simple equation is guaranteed by a correct choice of dh or ds.

Unsteady flow

The Saint-Venant equations describe the unsteady flow situation (Sturm, 2001, Brunner, 1995 #63):

$$\frac{\partial Q}{\partial x} + B\frac{\partial h}{\partial t} = q$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) = gA\left(S_0 - S_f - \frac{\partial h}{\partial x}\right) + q\frac{Q}{A}$$

Energy equation:

$$Z_2 + Y_2 + \frac{a_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{a_1 V_1^2}{2g} + h_e$$

Where:

Z_1, Z_2 = elevation of the main channel

Y_1, Y_2 = depth of water at cross sections

V_1, V_2 = average velocities

α_1, α_2 = velocity weighing coefficients

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