

# Discharge and location dependency of calibrated main channel roughness

## Case study on the River Waal

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**Abstract.** To accurately predict water levels, river models require an appropriate description of the hydraulic roughness. The bed roughness increases as river dunes grow with increasing discharge and the roughness depends on differences in channel width, bed level and bed sediment. Therefore, we hypothesize that the calibrated main channel roughness coefficient is most sensitive to the discharge and location in longitudinal direction of the river. The roughness is determined by calibrating the Manning coefficient of the main channel in a 1D hydrodynamic model. The River Waal in the Netherlands is used as a case study. Results show that the calibrated roughness is mainly sensitive to discharge. Especially the transition from bankfull to flood stage and effects of floodplain compartmentation are important features to consider in the calibration as these produce more accurate water level predictions. Moreover, the downstream boundary condition also has a large effect on the calibrated roughness values near the boundary.

## 1 Introduction

Hydrodynamic river models are used to predict water levels along the river and support decision making in river management. The models are used to monitor the river and to study the effects of measures in the river to decrease the risk of flooding in high water situations and prevent drought in low water situations. Therefore, the model predictions need to be sufficiently accurate. Insufficiently accurate predictions may lead to wrong decisions which in turn can lead to major damages and casualties in case of flooding.

Hydrodynamic models are calibrated and validated to increase accuracy. Calibration involves minimizing the error between prediction and observation by altering model parameters. Validation involves verifying whether the calibrated model parameters also produce minimal error between prediction and observation in different models. In most calibration studies of hydrodynamic models, the hydraulic roughness coefficient is calibrated because it is the most uncertain parameter [1]. However, this parameter is often treated as a dustbin to capture both the physical phenomena affecting the roughness but also model errors [2].

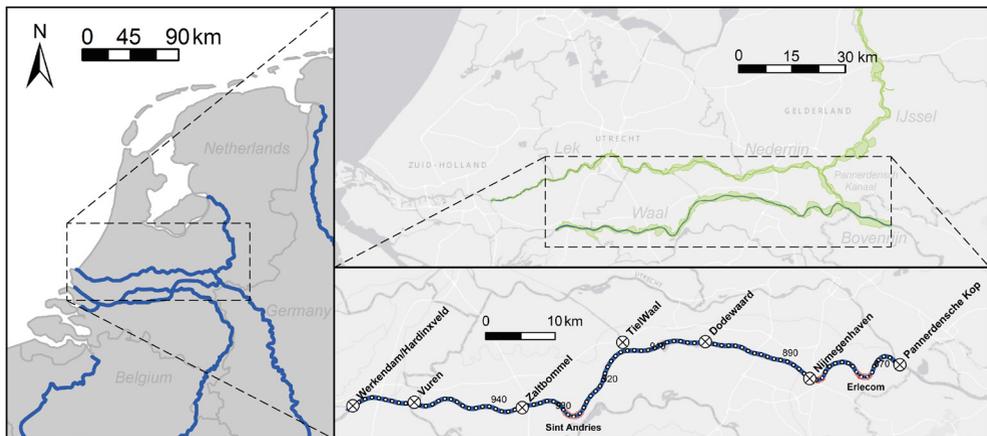
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Both the physical and calibrated bed roughness can vary along the longitudinal direction of the river due to differences in main channel and floodplain width, bed level and bed sediment. Furthermore, as discharge increases, river dunes grow in the main channel leading to an increased form drag [3]. Moreover, this increasing form drag also increases the bed roughness amongst other reasons. However, as the floodplain is flooded at a certain discharge, the interaction between the conveyance in the main channel and floodplain becomes more important. Therefore, it is expected to the hydraulic roughness is mostly dependent on the location in the river and the discharge. However, the study of [4] points out that the calibrated roughness does not necessarily have show the expected variations based on the mentioned reasons because calibration also involves compensating for model errors or errors induced by the calibration method. Therefore, it remains unclear which features of the calibrated roughness are physically or model error driven.

The main objective in this study is to investigate the location and discharge dependency of the main channel roughness by calibration and identify why differences between the physical roughness and the calibrated roughness occurs. Validation is performed to check if the calibrated roughness also results in accurate water level predictions. We use a case study on the River Waal in The Netherlands. The conclusions of this study can help to improve the water level prediction accuracy of 1D hydrodynamic models.

## 2 Study area: River Waal



**Figure 1.** Geographic overview of the River Waal in the Netherlands. Round crossed circles indicate observation station locations. Small white points along the river length are one kilometer spaced apart. Red highlighted river section in bends of the Waal indicate the location of submerged groynes and artificial armoured bed layers.

Figure 1 presents a geographical overview of the River Waal. The Waal is a distributary of the River Rhine in the Netherlands. Along the Waal, seven water level observation stations are operational. Station Dodewaard is only operational since 2001. The river is relatively straight with an average sinuosity of 1.1 [3]. The average main channel width is 260 m [5] which doubles near the downstream boundary at Werkendam. The floodplain width varies between 500 and 2500 m. The river has an average bed slope of  $1.05 \cdot 10^{-4}$  m/m. The average discharge entering the Waal after the “Pannerdenschekop” bifurcation is  $1500 \text{ m}^3/\text{s}$ .

The river bed mainly consists of sand with a typical grain size  $D_{50} = 1.0$  mm [5]. This corresponds to a Manning roughness value of approximately  $0.03 \text{ s}\cdot\text{m}^{-1/3}$  [3]. In the Waal river dune bed forms are present. These dunes grow in length and height in turn leading to an increasing bed roughness [3, 5]. In 1988 and 1999 artificial armoured bed layers at Nijmegen and Sint Andries were constructed to stall erosion of the outer bend. In 1996 submerged groynes at Erlecom were constructed to improve the navigability of ships. Additional large-scale interventions for flood risk reduction took place between 2007 and 2017.

The Waal has floodplain compartmentation in the longitudinal direction of the river which is typical for rivers in the Netherlands. This means that there exists a physical man-made barrier (a so-called summer dike) between the main channel and floodplain. Therefore, the water level must exceed the crest level of this barrier to flow into the floodplain. Floodplain compartmentation is parameterized as a volume correction [6].

### 3 Method

#### 3.1 Location dependency

The hydraulic roughness along the longitudinal direction of the river can be expressed using multiple roughness trajectories. A roughness trajectory is defined between two observation stations to avoid over-parametrization in the calibration. The roughness value of a trajectory is taken to be uniform along the whole trajectory. Roughness trajectories in the Waal model are correlated to each other because of the subcritical flow in the Waal. Therefore, downstream effects can propagate upstream. The location dependency is investigated using a varying number of roughness trajectories of roughly equal length. Five roughness trajectories are possible, since there are six observation stations available. We vary the number of trajectories with  $N = [1, 2, 4, 5]$ . To investigate the location dependency for different discharge stages, two discharge stages are calibrated (as illustrated in Figure 2): 1) bankfull stage and 2) flood stage. Only the top of the peaks are considered where the water level is roughly constant. Therefore, a discharge window around the discharge levels is applied.

#### 3.2 Discharge dependency

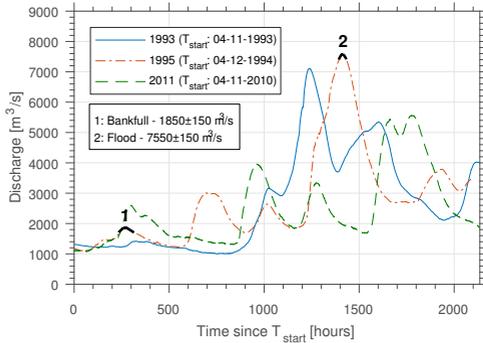
The calibration discharge stage is referred to as a discharge level. The discharge dependency is investigated using a varying number of discharge levels. The hydraulic roughness coefficient is described by an empirical linear tabular function dependent on the discharge. We vary the number of these discharge levels evenly over the discharge range with  $N = [2, 3, 4, 6, 8, 12]$ . The minimum discharge level is fixed at 1000 and the maximum at  $8000 \text{ m}^3/\text{s}$ . All discharge levels are calibrated in one calibration run. The whole three month time period of the 1995 discharge wave is used for calibration together with the maximum of five roughness trajectories.

#### 3.3 Calibration of 1D hydrodynamic model

The Dutch Ministry for Infrastructure and Environment maintains 1D and 2D models for all major Dutch rivers. For this study we use 1D hydrodynamic river models developed in the SOBEK 3 modelling program, because we need small computational times to perform multiple calibration runs. The cross-section geometry and floodplain roughness coefficients in the 1D model is derived from the 2D model [10], while the main channel roughness is used as a calibration parameter.

Three models are used following the calibration and validation periods: winter of 1995 for calibration and winters of 1993 and 2011 for validation. The discharge waves of these periods are presented in Figure 2. The Manning roughness formula is used because it is better suited for compound channels [7].

We use all observation data for every calibration run. The observation station at the downstream boundary is excluded because the observation data of this station is used as the downstream boundary condition. The software package OpenDA [8] is used to automatically calibrate the model with the DuD optimization algorithm [8, 9] and a weighted nonlinear least squares objective function.



**Figure 2.** Discharge waves of 1993, 1995 and 2011 for the Pannerdensche Kop location. Bankfull and flood stage discharge levels with discharge window used in location dependency calibrations are indicated by the black lines.

### 3.4 Validation

Validation is performed to identify which calibrated roughness provides the best water level predictions and is performed on the whole three month time period of the 1995 discharge wave and the two other discharge waves of 1993 and 2011 (as illustrated in Figure 2).

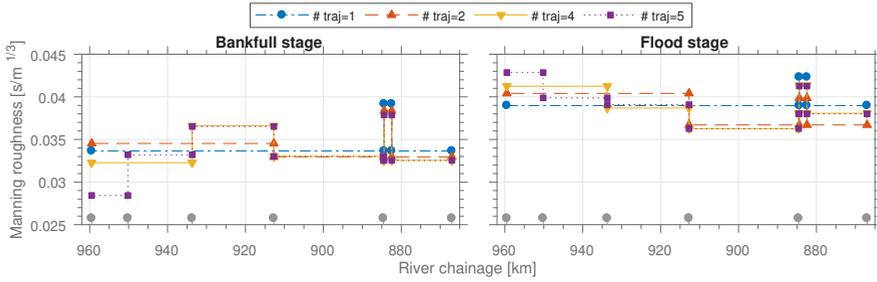
The RMSE criterion is used for validation because of the mathematical similarity with the used objective function for calibration. The whole time period of the discharge wave is used for validation. The RMSE-criterion is slightly adapted by multiplying it with a weighting factor  $\gamma$  to account for the more frequent low water levels and less frequent high water levels so every water level stage has an equal weight in the validation.

## 4 Results: Calibrated roughness

### 4.1 Calibrated roughness location dependency

Figure 3 presents the calibrated roughness for both bankfull and flood stage discharge level for varying number of roughness trajectories. The increase in roughness at river kilometre 882 is due to the artificial armoured bed layer at Nijmegen. This artificial armoured bed layer is calibrated using the approach by [11]. The calibrated roughness for the flood stage is higher than for the bankfull stage.

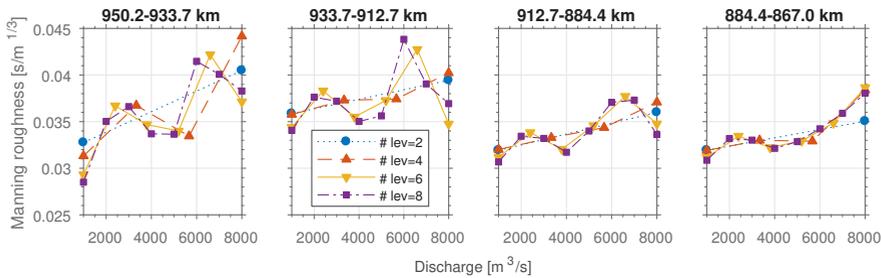
The roughness difference near the downstream boundary, starting from river kilometre 933, is possibly the result of an incorrect boundary condition. The backwater effect induced by the boundary condition under- or overestimates the water level at observation point Vuren at river kilometre 950. Calibration compensates for this by decreasing or increasing the roughness depending on the used discharge level.



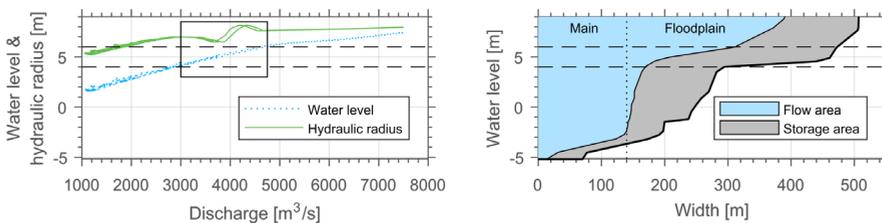
**Figure 3.** Calibrated roughness for varying number of roughness trajectories and for both bankfull and flood stage discharge level. The grey dots right above the x-axis show observation station locations.

### 4.2 Calibrated roughness discharge dependency

Figure 4 presents the calibrated roughness-discharge functions for the five roughness trajectories for  $N = [2, 4, 6, 8]$  discharge levels. Overall, the calibrated roughness increases as the discharge increases. However, more details appear if more discharge levels are calibrated.



**Figure 4.** Calibrated roughness-discharge functions for varying number of discharge levels for the River Waal. From right to left plots show the functions from upstream to downstream sections between measurement stations. The most downstream section is not shown, because results are largely affected by the downstream boundary condition.



**Figure 5.** Water level and hydraulic radius at location Zaltbommel (935 km) in the River Waal compared to the symmetric cross-sectionprofile. Transition zone of bankfull to flood stage indicated by dashed line.

These details show at low discharge a sharp roughness increase, after which it decreases. Then it shows a high roughness. The first roughness increase may be caused by growing

river dunes which increases the bed roughness. However, the roughness decrease and peak at higher discharge cannot be explained by bed-form dynamics.

The roughness decrease can be attributed to the transition from bankfull stage to flood stage. During this transition the hydraulic radius decreases suddenly (as presented in Figure 5). This leads to a lowered compound roughness. However, this lowering is not enough and thus the calibrated main channel roughness decreases. This effect is well-known in literature (e.g. [2])

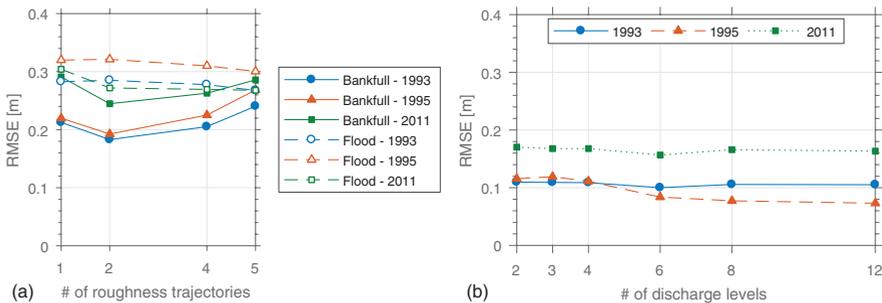
The roughness peak (around  $6000 \text{ m}^3/\text{s}$  in Figure 4) is a result of floodplain compartmentation. The compartmentation is parameterized as a volumetric correction. In reality during the large discharge peak of 1995, openings in the barrier creating the compartmentation (i.e. summer dike) are opened. This creates a discrepancy between the predictions and observations for which the calibrated roughness compensates.

At this discharge stage the interaction between main channel and floodplain also becomes increasingly more important. However, no measurements of the distribution of conveyance over the main channel and floodplain are done. Therefore, the effect of the interaction between main channel and floodplain at the flood discharge stage is unknown and investigation this interaction is recommended [12].

## 5 Results: Validation

### 5.1 Location dependency validation

Figure 6a presents the validation results of the location dependent cases. The results of all three bankfull cases show a minimum RMSE (and thus the most accurate water level predictions) when using two roughness trajectories. However, for the three flood cases no minimum RMSE is present because the RMSE still decreases with increasing number of roughness trajectories. Therefore, it is unclear which number of roughness trajectories produces a minimum error between water level predictions and observations when the whole water level range is considered equally important.



**Figure 6.** Validation of (a) location dependent calibrations and (b) discharge dependent calibrations.

### 5.2 Discharge dependency validation

Figure 6b presents the validation results of the discharge dependent cases. The RMSE of all instances are lower than the lowest RMSE in the location dependency cases (see Figure 6a). Making the hydraulic roughness coefficient a function of the discharge with only two discharge levels already results in more accurate water level predictions than all location

dependent cases. Therefore, it can be concluded that accuracy of water level predictions depends more on the number of discharge levels than on the number of roughness trajectories.

Both the 1993 and 2011 cases show a minimum RMSE value at six discharge levels. This corresponds to the calibrated roughness-discharge function where the transition from bankfull to flood stage and the floodplain compartmentation are captured. However, improvement in accuracy of water level predictions between two and six discharge levels is roughly 9% and thus minimal.

## 6 Discussion

The calibrated roughness at higher discharges is largely influenced by the compartmentation of the floodplain. Part of the overall roughness increase for the whole discharge range is an indicator for the growth of river dunes. But other parts are successfully identified in this study as a consequence of model errors. To investigate how great the effect of the floodplain compartmentation is, we suggest to perform this study with a river similar to the Waal but where no compartmentation of the floodplain is present. This proposed study could help aid in the development of roughness prediction models based on river bed forms (e.g. [13]).

All the results presented in this paper are obtained with 1D models. However, as 2D models are commonly used too, it is interesting whether the 1D results are representative for the 2D results. It is expected that the calibrated roughness for 2D models is mainly discharge dependent too. However, it is expected that the calibrated roughness-discharge functions lack the transition from bankfull to flood stage and the floodplain compartmentation because 2D models do not use a compound roughness and can model floodplain compartmentation more accurately.

## 7 Conclusion

The location and discharge dependency of the calibrated main channel roughness expressed by the Manning coefficient is studied using a case study on the River Waal in the Netherlands. The results show that the calibrated main channel roughness is mostly dependent on the discharge. Increasing roughness can be observed at lower discharges and maybe due to river dune growth. During the transition from bankfull to flood stage a roughness decrease is observed to compensate for model deficiencies. And at higher discharges a roughness peak occurs due to the floodplain compartmentation. However, as the calibrated roughness increases overall with increasing discharge, it is believed that the effect of river dune growth is also present in the calibrated roughness at higher discharges. In case of the location dependency, the difference in roughness values can mostly be attributed to an incorrect downstream boundary condition.

Validation results confirms that the calibrated main channel roughness is mostly discharge dependent. The calculated RMSE values of the location dependency calibrations show a large difference between the used discharge stage (i.e. bankfull or flood). These values are also higher than the RMSE values of the discharge dependency calibrations.

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