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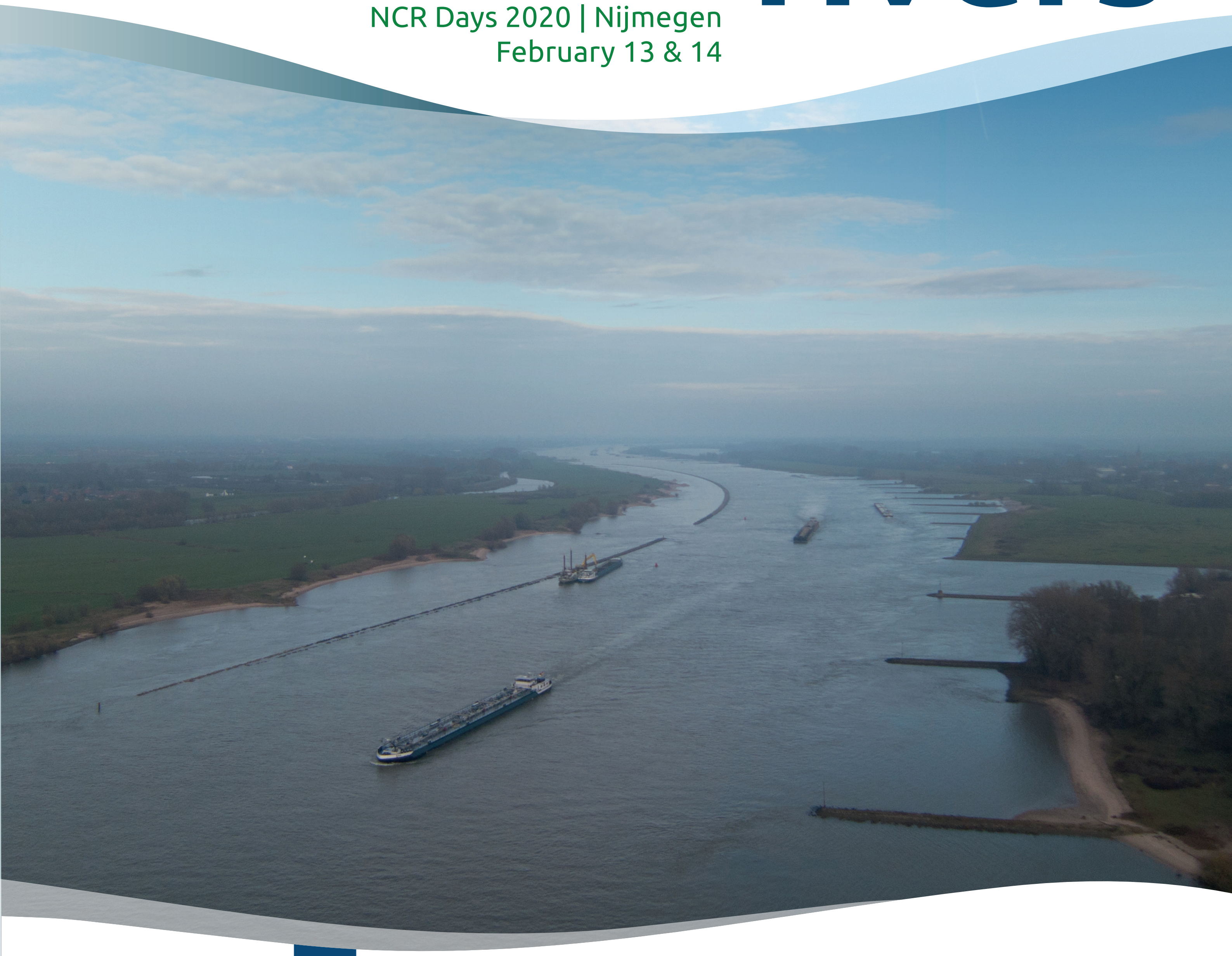

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A systematic error in the water balance of the Dutch river Rhine

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Introduction

Accurate rating curves are essential for flood management. It is unknown how the Dutch river Rhine system behaves at extremely high discharges. To predict this behaviour, hydrodynamic models are used which are calibrated and validated by rating curves. Rating curve accuracy is therefore important for the reliability of hydrodynamic model results and in turn flood management.

In our research we consider the three largest Dutch river Rhine branches, namely Bovenrijn (BR), Waal (WL) and Pannerdensch Kanaal (PK), and their bifurcation point Pannerdensche Kop. The locations are only 5 km apart without intermediate tributaries or significant water storage areas. Therefore, between the stations a nearly perfect water balance would be expected. Comparing the official rating curves of 2018 for these branches shows that the water balance is not closing, up to 5% error (Figure 1). The error is calculated as "(Q upstream – Q downstream) / Q downstream". A positive water balance error means that more water is entering the bifurcation than leaving.

Water balance error is a direct indication of the uncertainty of these rating curves and occurs since the water balance is not (sufficiently) considered in the establishment of rating curves. We aim to establish rating curves based on a closing water balance. Currently, in scientific literature, no method can be found that considers the water balance for the establishment of rating curves. Finally, we show how the found method influences the uncertainty bands of the rating curves.

Method

To evaluate the significance of the apparent water balance error we first quantify the

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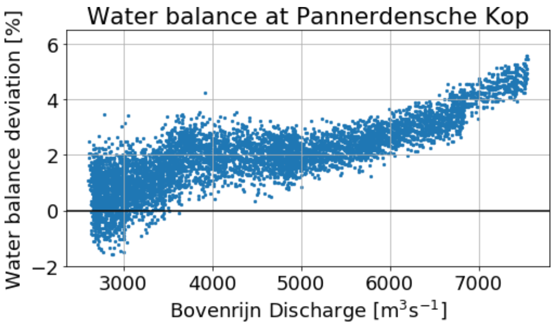

Figure 1. Water balance error at bifurcation Pannerdense Kop for discharge data derived from official rating curves (source: https://waterinfo.rws.nl/). The figure presents the discharge domain without weir effects for year 2018.

uncertainty that is associated with the individual rating curves. For this purpose, we use a dataset containing all available stage-discharge measurements over a period from 1988 to 2018. The data has been validated by data-owner Rijkswaterstaat, by which several outliers were removed from the data. To achieve a homogeneous data set, we excluded measurements influenced by weirs ($H_{Lobith} < 10$ m +NAP) and corrected for riverbed subsidence. Following Berends et al. (2019), who found that in the data there is no detectable effect of recent river interventions on water levels, we ignored river interventions. Also, due to time limitations we ignored hysteresis effects. Next, similar to Berends (2019), we quantify rating curve uncertainty using Bayesian inference and Markov chain Monte Carlo simulations, as based on the homogenized measurement data set. We now constructed rating curves by only using locally measured stage and discharge as input data, which is common practice.

In our new method we also include discharge measurements from other locations to incorporate a closing water balance in the separate rating curves in four steps. Firstly, we filter all measurements on the prerequisite that the measurements in all three branches coincide by day. This allows a comparison of the water balance of the discharge measurements. The available dataset contains 292 same-day discharge measurements. Secondly, the two non-local same-day discharges are summed or

Table 1. Water balance of same-day measurements

Considered location	Discharge	Water level
Lobith – BR	$Q_{WL} + Q_{PK}$	H_{Lobith}
Pann. Kop – WL	$Q_{BR} - Q_{PK}$	$H_{Pann.\,Kop}$
Pann. Kop – PK	$Q_{BR} - Q_{WL}$	$H_{Pann.\,Kop}$

subtracted depending on the water balance and the considered location for rating curve construction (Table 1). Thirdly, depending on the considered location, the 292 non-local calculated discharges are coupled with locally measured same-day water levels (Table 1). Per water level, we now have two same-day discharges, one locally measured and one calculated from two non-local measurements. Finally, we again quantify rating curve uncertainty using Bayesian inference and Markov chain Monte Carlo simulations.

Results

The rating curves of the new method have shifted as compared to the current method, giving slightly lower discharges at equal water level for the upstream location of Lobith and slightly higher discharge values for equal water levels at the two downstream locations (Figure

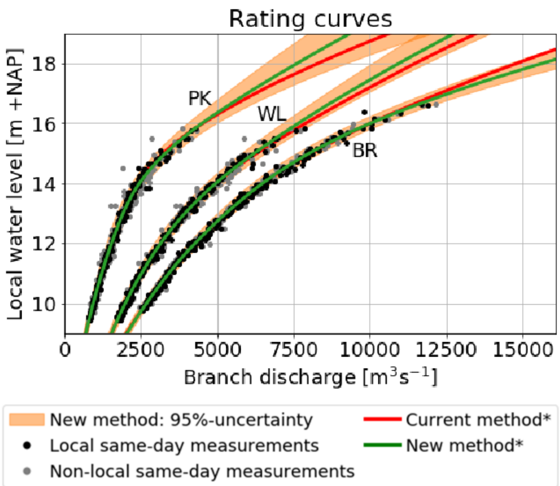

*Figure 2. Comparing current- and new method for rating curve construction (*max a posteriori estimation)*

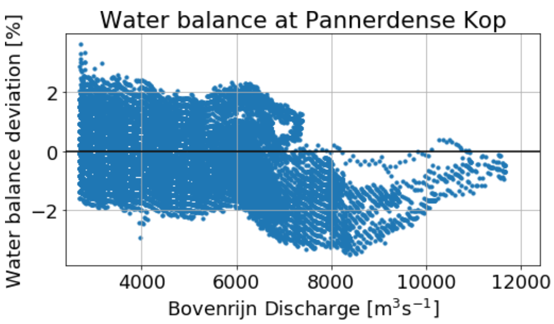

Figure 3. Water balance under the new rating curve method for observed water levels in the period from 1988 to 2018.

*Table 2. Influence of water balance consideration on rating curve uncertainty (*at 95% probability).*

Considered location	Current method Error [%]*	New method Error [%]*
Lobith – BR	± 4.94 %	± 5.02 %
Pann. Kop – WL	± 5.66 %	± 6.23 %
Pann. Kop – PK	± 6.53 %	± 8.70 %

2). Applying the new method to observed water levels shows that the pronounced bias in water balance is clearly reduced (Figure 3). However, this method created a larger spread in discharge data points leading to wider uncertainty bands around the rating curves, especially for the downstream branches (Table 2).

Conclusion and recommendations

Compared to current rating curve construction practice, our new method clearly reduced a systematic error in water balance and thereby provided more consistent rating curves for the river network of the Dutch Rhine. The trade-off of this improvement is that the uncertainty bands of the individual rating curves have increased. However, since rating curves are essential in the construction of discharge time-series from water levels and in the calibration of river models, it is important that systematic errors in rating curves are removed as much as possible. Especially if these discharge time-series and calibrated models are used to define and hydraulically model design flood events. In the Netherlands, the design discharge for the Rhine river network is far beyond any event that has ever been observed. It is therefore essential that models used for development of flood management and regulations do not contain systematic effects that distort realistic system behaviour. For future measurement campaigns, we recommend to improve the accuracy of consistent rating curves by taking more same-day discharge measurements.

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