Water balance in the Dutch river Rhine and rating curve uncertainty

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Water balance in the Dutch river Rhine and rating curve uncertainty

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ABSTRACT:

Accurate rating curves are essential for a wide range of river management purposes, particularly as a basis for flood risk management. In our research, we investigate rating curve uncertainties as related to flow measurement errors. We consider the three largest Dutch river Rhine branches (Bovenrijn, Waal and Pannerdensch Kanaal) and the bifurcation point Pannerdense Kop. Comparing the official rating curves for these river channels shows that the water balance is not closing (up to 5% deviation), and this gives a direct indication of the uncertainty in the rating curves. We quantify rating curve uncertainty using Bayesian inference and Markov chain Monte Carlo simulations, as based on homogenous measurement data sets. Next, we show how water balance considerations can influence the uncertainty of rating curves. Finally, we discuss implications for current flood risk norms in the Netherlands and implications for future hydrometric campaigns.

1 INTRODUCTION

Discharge time-series are a key 'variable' in river water management as they form essential input to a variety of functions and objectives, spanning from flood and drought management to ecological studies and waterborne traffic (Quartel et al., 2011; Le Coz, 2012). However, discharge measurements in rivers are difficult to obtain and therefore the most common method to create discharge time-series is to measure water levels and translate these to discharge values using a rating curve. The traditional method for obtaining rating curves is to fit a curve through paired measurements of water stage h and discharge Q for a particular location along the river (Kean & Smith, 2010). Typically, such rating curves ignore seasonal effects (vegetation and ice cover), they do not include hysteresis and it is rarely specified to which specific river characteristics they apply. For example, those characteristics could include channel geometry, human interventions and rate of riverbed subsidence, which can all affect the rating curve (Herschy, 2009). In the Netherlands, to generalize and improve accuracy of rating curves so-called "Qf-relationships" are established that correct for: 1) hysteresis, 2) autonomous subsidence (large-scale bed level changes), 3) weir effects and 4) human interventions to the river (HKV, 2016).

Because of the demanding efforts for data collection and processing in setting up rating curves, they are often created only at relatively few key river locations. Along a single river reach, consecutive rating curve locations are commonly far between, because it is assumed that in a single channel the intermediate discharge-variations are small. An exception to this is when tributaries or bifurcations are present in the river. Rating curves in different reaches and different branches are then required to fully describe the distribution of water over the river branches. Together, these rating curves in a network should give a closing water balance, where water input from upstream is traceable to downstream, apart from intermediate minor additional runoff, inflows, or stored or extracted water quantities. In this study we aim to understand uncertainty in the rating curves and explore the effect of imposing a closing water balance when establishing rating curves.

2 WATER BALANCE AROUND A RIVER BIFURCATION

In the Netherlands, a great opportunity presents itself to check the consistency and accuracy of rating curves at river stations around the bifurcation near the Pannerdense Kop, see Figure 1. This location in the river Rhine is of great significance for water management in the Netherlands. Amongst others, the discharge split at the Pannerdense Kop affects downstream flood risk, and it is actively controlled to aid river navigation. Therefore, the discharge split at the Pannerdense Kop is frequently measured: at a location just upstream of the bifurcation point and at two locations in each of the downstream branches (in river Waal and Pannerdensch Kanaal, see inset in Figure 1). 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.

Figure 2 shows the calculated error in the water balance at this bifurcation point, as derived from rating curves at three locations, and from actual ADCP measurements that were carried out in 2018. Only data for water levels above 10 m +NAP at Lobith were considered, which is the regime of a freely flowing river where no active weir operating is taking place (Reeze et al., 2017). This threshold of 10 m +NAP at Lobith roughly corresponds with an upstream discharge of 2500 m^3s^{-1}. The systematic positive error of up to 5% reflects a *higher* upstream water volume, implying that in the bifurcating system water is lost. No physical explanation is known for this observation, and therefore we consider this an indication of the inaccuracy of the respective rating curves.

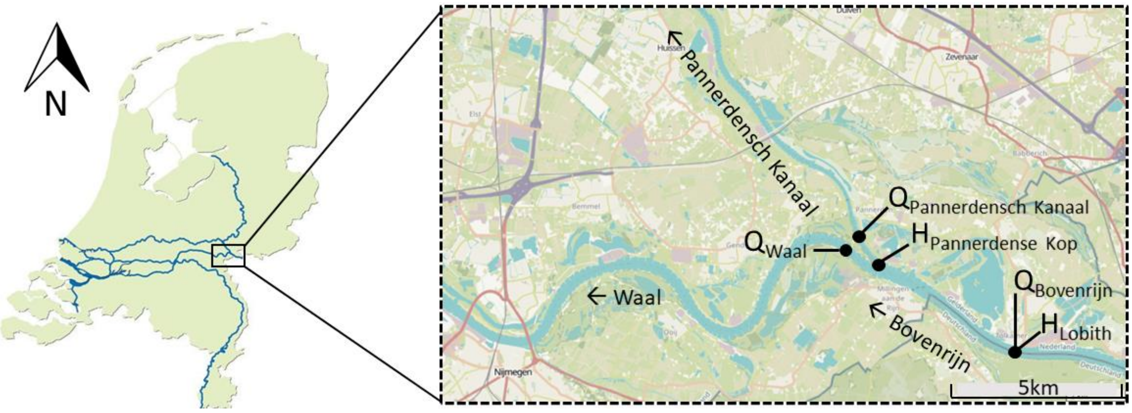

Figure 1. The Rhine river in the Netherlands near the bifurcation point at Pannerdense Kop. Also shown are the three rating curve locations. Adapted from Steenblik et al (2020).

3 UNCERTAINTY OF RATING CURVES

To evaluate the significance of the apparent water balance error shown in Figure 2 we first quantify the uncertainty that is associated with the individual rating curves. For this purpose, we use a dataset containing all available discharge measurements over a period from 1988 to 2018. The measurements have been collected at Lobith (Bovenrijn) and at the bifurcation Pannerdense Kop (Waal and Pannerdensch Kanaal), at each location having 1303, 1202 and 1520 measurements, respectively. Each datapoint consists of three components: timestamp, measured stage and measured discharge. The stage has been measured continually with respect to the Amsterdam Ordnance Datum (NAP), using automatic float driven shaft encoders (Buschman et al., 2017). The discharge has been measured infrequently, using helical Ott-mills (mechanical hydrometric current meters) between 1988-2004 and Acoustic Doppler Current Profilers (ADCP) between 2001-2018. The data has been validated by data-owner Rijkswaterstaat, by which several unrealistic outliers were removed from the data.

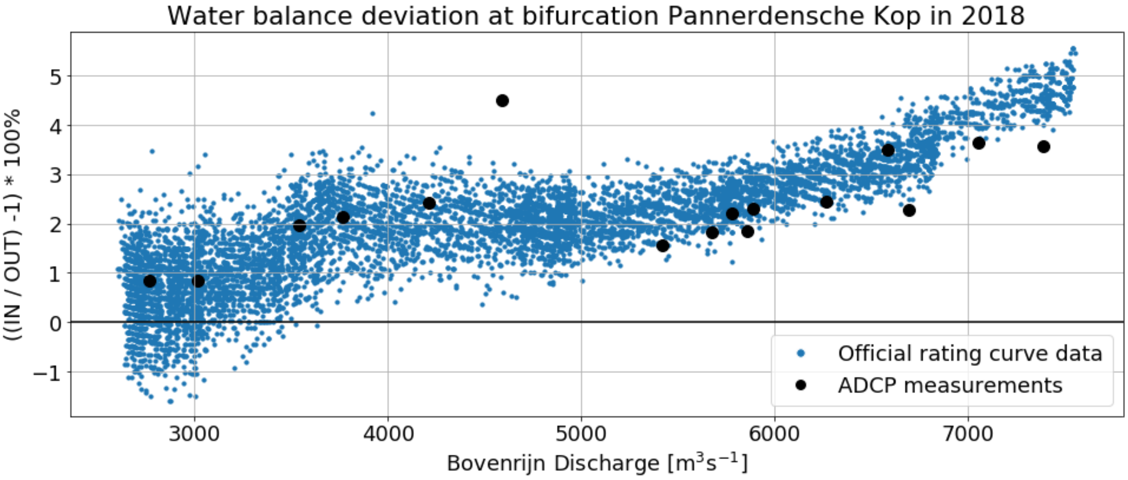

Figure 2. Water balance deviation for Qf derived data and ADCP measurement data in 2018.

To achieve a homogeneous data set, we first excluded measurements influenced by weirs (leaving only points where the water levels at Lobith are above 10 m +NAP). Next, we corrected for riverbed subsidence by detrending the measured water levels for equal discharges, see Figure 3. For all three branches, water levels have visibly lowered for equal discharges due to riverbed subsidence, up to roughly 0.6 m within the entire study period. 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.

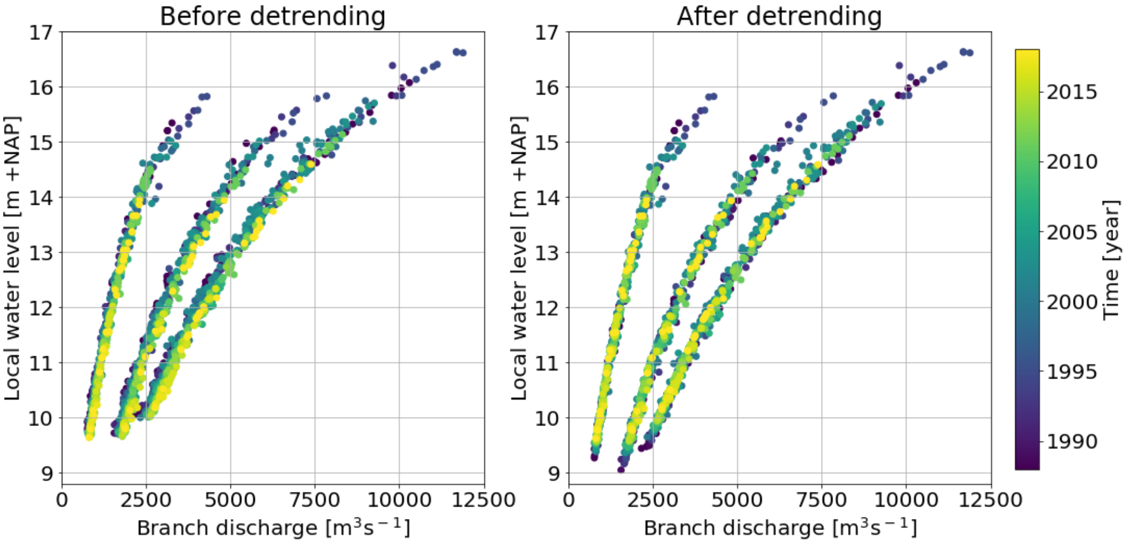

Figure 3. Result of correcting for riverbed subsidence by detrending the measured water levels for equal discharges, which removed the time-dependency reduced the spread. The left plot shows the measurements before detrending and the right plot shows the measurements after detrending.

Next, similar to Berends (2020), we quantify rating curve uncertainty using Bayesian inference and Markov chain Monte Carlo (MCMC) simulations, as based on the homogenized measurement data set.

The rating curve model used in this research is a summation of the one-dimensional power function adopted from WMO (2010) and ISO (2010). The model is derived from the Manning-

Strickler equation and assumes a steady uniform flow in a wide rectangular channel. The model is given as:

$$Q = \sum_{i=0}^{N} a_i \, (h - b_i)^{+p_i}, \;\; h > b_i \qquad (1)$$

where the measured water level $h\,[m + NAP]$ serves as input to derive the total discharge $Q\,[m^3 s^{-1}]$. The model parameters are the bed level $b\,[m + NAP]$, the parameter related to the channel characteristics $a\,[m^{4/3} s^{-1}]$ and the hydraulic exponent $p\,[-]$. Furthermore, the discharge is computed from a summation following the division of the channel cross-section in a number of $N\,[-]$ subsections $i\,[-]$. Following HKV (2009), three subsections are assumed, representing the equivalent of the main channel, groin fields and flood plains.

Based on ISO (2007) for Ott-mills and ISO (2012) for ADCP, we assume that the distribution of the discharge measurement errors are of normal nature. Therefore, a Normal error model proportional to the discharge is used to formalize the relationship between stage and discharge. Assuming that errors in stage measurement are negligible, the error model is given as:

$$Q(h|\theta, \sigma) = f(h|\theta) + \epsilon \qquad (2)$$

$$\epsilon \sim N\big(0, \sigma f(h|\theta)\big) \qquad (3)$$

where $f(h|\theta)$ is the rating curve model (Equation 1) with rating curve parameters θ. The normal error term ϵ is a Normal distribution around $f(h|\theta)$ (no bias), with relative standard deviation σ. The rating curve parameters θ and the relative standard deviation σ are unknown stochastic values and are optimized using Bayesian inference and MCMC (using the Hamiltonian No-U-Turn sampler (NUTS) (Hoffman & Gelman, 2014). More details on the statistical optimization procedure can be found in Twijnstra (2020).

The maximum a posteriori (MAP) rating curves that result from the optimization procedure are plotted in Figure 4, representing the modus of the probabilistic rating curve. Using MAP value is a standard choice in Bayesian statistics (Mansanarez, 2016). In the obtained rating curves, it is visible that for large parts of the curve the 95% uncertainty bands are relatively narrow. The 95% uncertainty bandwidth at local water levels of 12 m +NAP are around 430 m^3s^{-1}, 365 m^3s^{-1}, 200 m^3s^{-1} for the branches, Bovenrijn, Waal, Pannerdensch Kanaal, respectively. The uncertainty of the extrapolated rating curve rapidly widens.

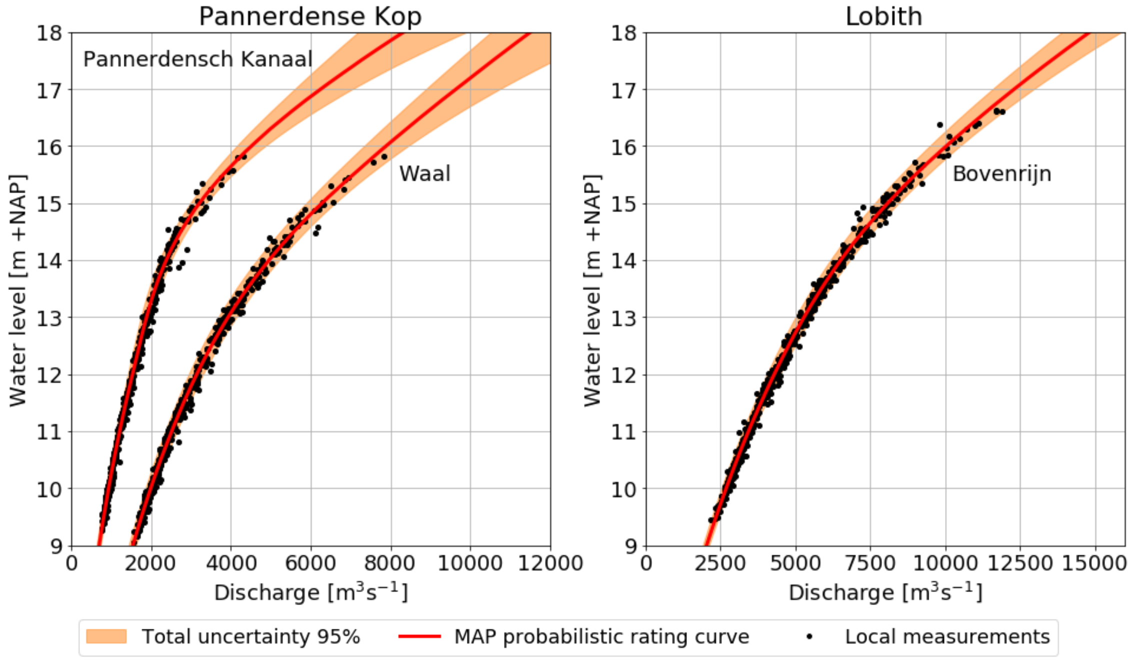

Figure 4. Rating curves based on homogeneous locally measured data.

4 USING WATER BALANCE IN RATING CURVE

In the previous section, rating curves were constructed by only using locally measured stage and discharge as input data. In our new method we also include discharge measurements from other locations to incorporate a closing water balance in the separate rating curves. In Figure 2 it was shown that the original rating curves give a systematic error in water balance. However, we do not know which of the three rating curves is most reliable and which of the three contribute(s) most to the water balance error. Therefore, we treat all three locations as equally reliable and propose a method in which for each location data from the other two locations is used to adjust for water balance-offset in the rating curves.

To illustrate this method, we pick Lobith as example location. First, we filter the data previously used in Section 3 on the prerequisite that a water level and discharge measurement is available in each of the three branches within the same day. This allows a same-day comparison of the water balance of the discharge measurements for each data point. The resulting filtered dataset contains 292 same-day discharge and water level measurements for each of the three locations. Second, for the upstream location of Lobith, we sum the same-day discharge measurements of the two downstream bifurcating branches and couple these summed measurements with the same-day water levels at Lobith. The resulting 292 calculated data points are added to the 292 locally measured same-day stage-discharge data at Lobith. Per water level point, we now have two same-day discharges values, one local and one non-local, yielding a total of 584 data points. We use this same approach to also construct 584 local and calculated data points for the two downstream locations. See Table 1 for an overview of how for each station additional data points were calculated based on a water balance.

By using same-day measurements, variation in discharge and water level in time and space is avoided. We assume that the temporal variation is small, because the river Rhine is a delta river and the maximum rate of change of discharge is roughly 20 m^3s^{-1} per hour. Also, the same-day measurements are taken in a small time window, namely between 08:00 and 17:00. Furthermore, we assume that the variation in space is small, since the distance between Lobith and Pannerdense Kop is only 5 km, see Figure 1. Furthermore, for the water level, there exists a strong linear correlation, namely r^2=0.9989, between the same-day water level measurements at Lobith and Pannerdense Kop.

Finally, similar to the method used in Section 3, we construct Bayesian rating curves. The results are shown in Figure 5, where among the data points the non-local calculated data points are plotted in grey. It appears that the rating curves in Figure 5 have now shifted as compared to Figure 4, 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. A repetition of the analysis from Figure 2 shows that no longer a clearly pronounced bias in water balance is present, see Figure 6. Adding the calculated data points to the analysis corrected for bias in water balance. However, this method created a large spread in data points leading to wider uncertainty bands around the rating curve, see Table 2. Note that some ‘non local’ data points appear to be quite uncertain, which is the result of combined uncertainties from the two measurement locations. Also, uncertainties in rating curve have mostly increased in the downstream branches.

Table 1. Non-local same-day measurements.

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

Table 2. Influence water balance consideration on rating curve uncertainty

Considered location	**Current method (Figure 4)** Relative error at 95% probability	**New method (Figure 5)** Relative error at 95% probability
Lobith – Bovenrijn	±4.94 %	±5.02 %
Pann. Kop – Waal	±5.66 %	±6.23 %
Pann. Kop – Pann. Kanaal	±6.53 %	±8.70 %

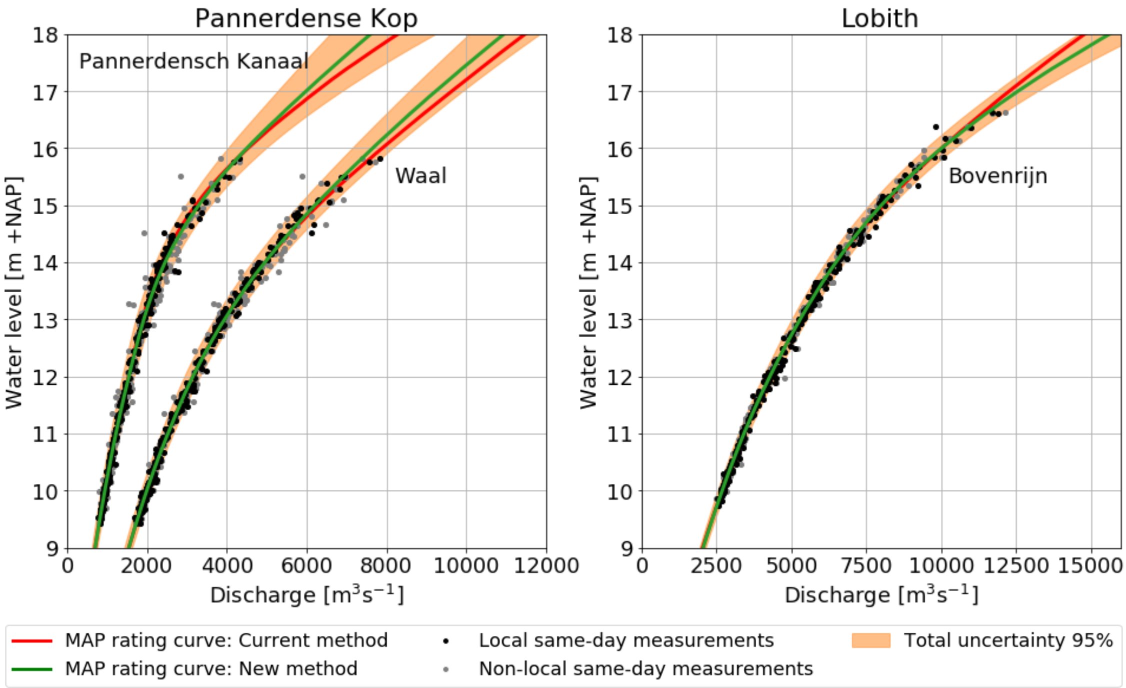

Figure 5. Rating curve based on water balance closure, including MAP rating curve (in red) of Figure 4.

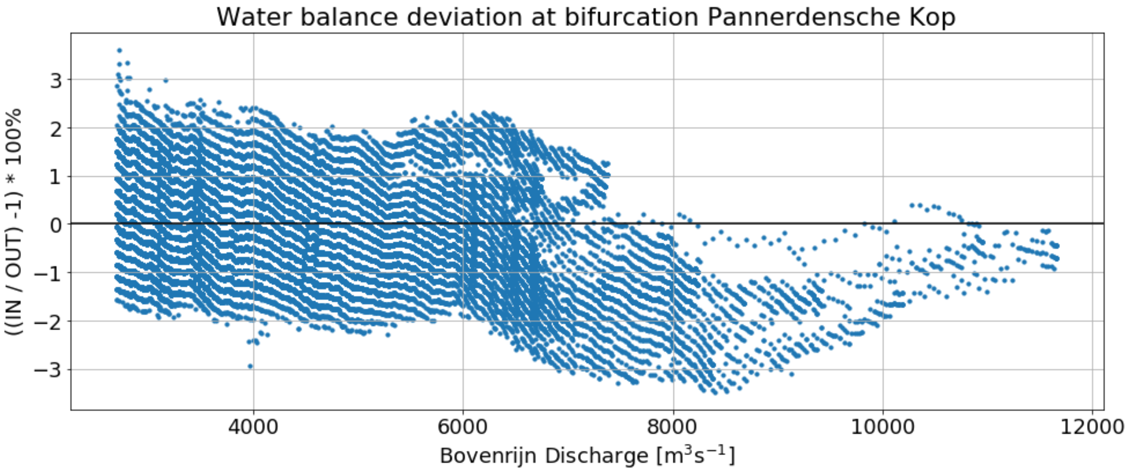

Figure 6. Repetition of Figure 2 using the new rating curve method for observed water levels in the period from 1988 to 2018.

5 CONCLUSIONS AND RECOMMENDATIONS

In this paper we presented a new method for establishing rating curves based on water balance closure. Compared to the method used in todays practice, our new method removes a systematic error in water balance and thereby it provides 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. Therefore, it of important that models used for development of flood management norms and regulations do not contain systematic effects that distort realistic system behavior. For future measurement campaigns, we recommend to improve the accuracy of consistent rating curves by taking more same-day measurements. Also, discharge measurements at other locations could be compared to get more insight in discharge reliability per river branch. Unfortunately, such additional locations are only few in the Rhine branches, and they are far between. We recommend to apply the new method to the other bifurcation in the Rhine branches (at the IJsselkop) as well.

6 ACKNOWLEDGEMENTS

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