Stormflow and suspended sediment routing through a small detention pond with uncertain discharge rating curves

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ABSTRACT

Ratings curves are commonly used for computing discharge time series from recorded water stages or for hydrograph and sediment graph routing through detention ponds. Numerous studies have demonstrated that these rating curves are often linked with significant uncertainty. Nevertheless, the uncertainty related to the use of these rating curves in sediment estimates has not been investigated so far. Hence, in this work, we assess the impact of using such uncertain discharge rating curves on the estimation of the pond outflow (discharge, sediment concentration and load) from a small detention pond located in a small urban catchment in Poland. Our results indicate that the uncertainty in rating curves has a huge impact on estimates of discharge and sediment fluxes in the outlet from the reservoir, wherein the uncertainty in the inlet rating curve plays a more important role than the uncertainty in the outlet rating curve. Poorly estimated rating curve(s) may thus lead to serious errors and biased conclusions in the estimates and designs of detention ponds. To reduce this uncertainty, more efforts should be made to construct the rating curves at the pond inlet and to gather more data in extreme conditions.

Key words | pond routing, rating curve, uncertainty analysis, urban catchment

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INTRODUCTION

Excessive sediment loads in urban rivers, among others, impair water quality, increase treatment costs and floodwater damage, or disturb the operation of impoundments and reduce the capacity of in-stream reservoirs (Guy 1970). Especially harmful to the environment is suspended sediment that sorbs and carries other associated pollutants, such as phosphates (Hejduk 2011), radionuclides (Walling 2006), and other toxic compounds (Sikorska *et al.* 2015). The most severe sediment related problem is however the general deterioration of the total environment.

The management of stormwater has undergone significant change over recent decades (Fletcher *et al.* 2015). To mitigate the aforementioned negative effects of extensive sediment loads, small (detention) ponds are often constructed at local urban streams (Verstraeten & Poesen 2000; Krajewski & Banasik 2017). By capturing and detaining the stormflow (direct runoff after heavy rainstorms), they reduce the peak flows and therewith the sediment loads and associated pollutants transported with stormwater. Such reservoirs have been shown to operate efficiently provided there are correct design criteria and regular maintenance (United States Environmental Protection Agency [USEPA] 1999). The operation of existing ponds may be assessed based on continuous monitoring of the inflow and the outflow from the reservoir (Krajewski *et al.* 2017b), which helps to plan future maintenance strategies. Currently, such field measurements are still rarely conducted in small urban catchments (Sikorska *et al.*

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2015), mostly due to limited human and financial resources. However, if only the inflow (discharge and sediment) to the reservoir is known, its outflow (discharge and sediment) may still be estimated based on the routing concept (Haan *et al.* 1994). Such a routing concept relates sediment loads at the outflow from the reservoir to its inflow and the characteristic detention time of the reservoir. As shown recently by Krajewski *et al.* (2017b), a few (in that case seven) recorded rainfall-stormwater-sediment events can be sufficient to estimate the relation between the inflow and the outflow sediment and therewith to calibrate such sediment routing models.

In practice, however, even if the discharge is known, it is usually estimated from the water stage (Sikorska *et al.* 2013; Requena *et al.* 2017). For computing discharge time series from recorded water stages and for hydrograph routing through a reservoir, rating curves (RCs) that link the discharge to the corresponding water stage at the cross-section are thus necessary (Le Coz *et al.* 2014). Such RCs should be established and regularly verified by field measurements. Nevertheless, even then, they are subject to uncertainty due to the chosen form of the curves (usually power law equations), errors in measurements of water stage-discharge pairs, seasonal changes in vegetation, sediment erosion or bedload transport, or unstable flow conditions at cross-sections (McMillan *et al.* 2012; McMillan & Westerberg 2015; Sikorska & Renard 2017). Hence, stormflow and sediment estimates that are based on rating curves are also subject to uncertainty. This uncertainty not only contributes to uncertain estimates of sediment fluxes in rivers and of sediment loads in the outflow from small detention ponds, but also impacts the accuracy of the calibration data for sediment routing models.

In this work, we therefore assess the impact of using such uncertain discharge rating curves on the estimation of the pond outflow (discharge, sediment concentration and load) from a small detention pond located in a small urban catchment in Poland. To this end, we first assess the uncertainty in rating curves and next propagate this uncertainty through the sediment routing model on the sediment estimates at the pond inlet and outlet. In this respect, we consider four different strategies of using such uncertain rating curves in sediment routing models: (a) only uncertain RC at the pond inlet, (b) only uncertain RC at the pond outlet, (c) uncertain RCs at both the pond inlet and outlet, and (0) no uncertainty in either the inlet or the outlet rating curve. While strategies (a) and (b) allow assessment of the relative importance of individual RCs, strategy (c) assesses the uncertainty in sediment loads due to their joint effect which does not have to be additive. Finally, by comparing with the strategy null (0), we assess the effect of neglecting the uncertainty in both rating curves. We further demonstrate how the uncertainty related to the use of such uncertain RCs can be quantified by using Monte Carlo simulations and by propagating prediction intervals of estimated RCs through the sediment routing model. Note however that the sediment routing model itself, developed recently by Krajewski *et al.* (2017a), is not the focus of this study.

The topic related to the uncertainty of the rating curve is not new and many investigations on it have already been conducted. Yet most of the previous studies focused on the importance of rating curve uncertainty for an estimation of discharge, and related to it: flood forecasting, rainfall – runoff modelling or water level predictions (Domeneghetti *et al.* 2012; Sellami *et al.* 2013; Sikorska *et al.* 2013; Ocio *et al.* 2017). The reason for this is that the use of the rating curve for a discharge estimation is its most direct and most frequent application. No less important, however, is the estimation of the rating curve uncertainty in the context of sediment modelling and sediment routing, although far fewer studies exist which analyse the impact of an uncertain rating curve on sediment estimates (Smith & Croke 2005; Schmelter *et al.* 2012). Such studies are needed as they help to improve the understanding of the sediment rating curve concept, i.e., the empirical relationship between the discharge and the amount of sediment transported in the runoff.

This paper tackles the issues related to the usage of rating curves in sediment estimates, namely in the routing of water and sediment through a small reservoir, which both rely on discharge and thus rating curve estimates. The major novelty of our work lies thus in proposing a feasible method to handle uncertainty in RCs within sediment routing models based on discharge computations and to quantify this uncertainty in sediment estimates. To the best of our knowledge, the issue of uncertain rating curves in estimates of such small detention ponds has not been investigated to date. Most previous works on uncertainty in sediment models have focused either on the parameter uncertainty (Ruark *et al.* 2011), or on the model structure and parameter uncertainty (Sabatine *et al.* 2015), while other uncertainty sources were not considered.

STUDY AREA

The study area is a small urban catchment of the Służew Creek, located in the south-west part of Warsaw in Poland (Figure 1). The area of the subcatchment up to its outlet to Wyścigi Pond is 28.7 km^2, with an impervious area fraction of 22% (Pietrak & Banasik 2009). Its northern part is strongly urbanized; the south is covered with single-family houses, fields, wastelands and woodlands. The topography is typical for a lowland area, e.g., the absolute relief equals 30 m, the slope of the main channel is 1.05 ‰.

The Wyścigi Pond is located directly at the stream and has an area of 1.3 ha and a volume of 14,500 m^3 (Krajewski *et al.* 2017b). As the previous research has shown, although the reservoir contributes negligibly to the stormflow reduction, it reduces meaningfully the load of transported sediment.

Hydrological monitoring of the catchment is carried out by the Department of Hydraulic Engineering of WULS-SGGW.

METHODS

Field measurements and data pre-processing

Two gauging stations are located upstream and downstream of the Wyścigi Pond, at which inflow and outflow from the pond are measured. These stations are equipped with staff gauges and water stage loggers, and are also adapted for collecting water and sediment samples. Water stages are recorded by automatic pressure loggers every 10 minutes and are also verified weekly with manual readings from staff gauges. Sediment samples are taken manually with 2–3 hour intervals during the passage of the stormflow, using a manual bathometer. This device consists of a 1-litre container and two pipes. One of them carries water with sediment into a container, while at the same time another pipe discharges air. The samples are collected after the passage of the flood wave and transported to the lab, where the concentration of suspended sediment in each sample is estimated by weighing its dried solid component. Discharge is periodically measured during high, medium and low water stages at the inflow and the outflow of the reservoir using the Acoustic Doppler Current Profiler – ADCP (Hejduk 2008), and corresponding water stages are estimated from staff gauges. Based on recorded stage-discharge pairs, rating curves are established which are then used for computation of the stream flow.

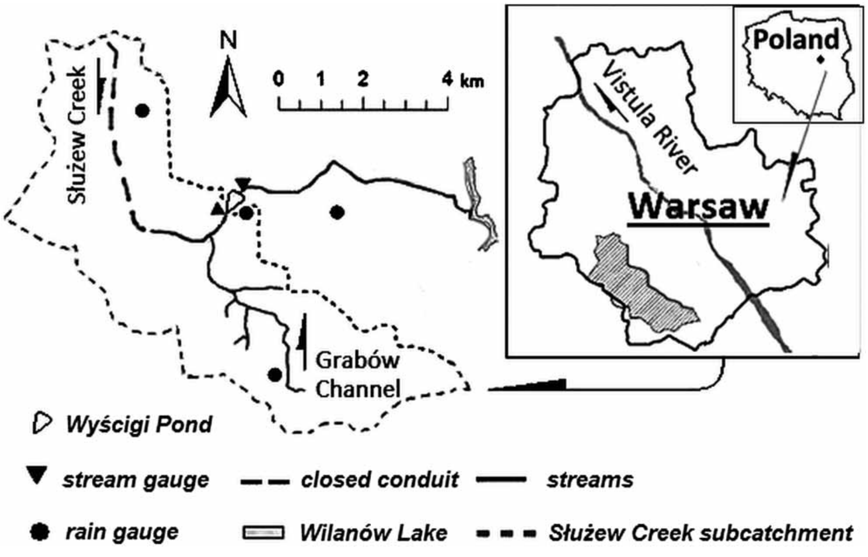

Figure 1 | Służew Creek catchment up to the outlet to Wyścigi Pond.

In addition to hydrological measurements, four tipping bucket rain gauges are placed in the catchment, which record each movement of the bucket, i.e., when rainfall of 0.1 mm has been collected. Rainfall depths are then summed up for 10-minute intervals. The average rainfall over the entire catchment is calculated according to the Thiessen polygons method.

More detailed information on the catchment and conducted investigations can be found in Sikorska *et al.* (2013, 2015), Banasik *et al.* (2014) or Krajewski *et al.* (2017a).

Description of the stormflow and sediment routing model

The process of hydrograph and sediment graph routing through the pond, here Wyścigi Pond, may be described with the use of flow and suspended sediment continuity equations (see Krajewski *et al.* (2017a) for a detailed model description):

$$\frac{dS}{dt} = I_{(t)} - O_{(t)} \tag{1}$$

$$\frac{d(VC^{II})}{dt} = I_{(t)}C^{I}_{(t)} - O_{(t)}C^{II}_{(t)} - K_{(T_d)}V_{(t)}C^{II}_{(t)} \tag{2}$$

where:

dS/dt – change in water storage ($m^3 \cdot s^{-1}$) at time t,
$I_{(t)}$ – inflow discharge ($m^3 \cdot s^{-1}$),
$O_{(t)}$ – outflow discharge ($m^3 \cdot s^{-1}$),
$d(VC^{II})/dt$ – change in the suspended sediment mass in the reservoir ($g \cdot s^{-1}$) at time t,
V – reservoir volume (m^3),
$C^{II}{}_{(t)}$ – suspended sediment concentration in the reservoir and in outflow ($mg \cdot dm^{-3}$),
$I_{(t)}C^{I}{}_{(t)}$ – suspended sediment mass entering reservoir ($g \cdot s^{-1}$),
$C^{I}{}_{(t)}$ – suspended sediment concentration in inflow ($mg \cdot dm^{-3}$),
$O_{(t)}C^{II}{}_{(t)}$ – suspended sediment mass leaving reservoir ($g \cdot s^{-1}$),
$K_{(T_d)}V_{(t)}C^{II}{}_{(t)}$ – mass of suspended sediment deposited in the reservoir ($g \cdot s^{-1}$),
$K_{(T_d)}$ – suspended sediment decay coefficient dependent on the detention time being also the single model parameter (s^{-1}).

Equation (1) is solved for discharge outflow which implies that the inflow hydrograph and stage-discharge-storage relationship must be known. Effluent concentration of the suspended sediment is determined based on Equation (2). Model inputs are: inflow and outflow hydrographs, inflow sediment graph, reservoir volume and decay coefficient. Krajewski *et al.* (2017a) have proposed a method to estimate the decay coefficient based on the detention time from the power formula:

$$K = 7.11 \cdot 10^{-5} \cdot T_d^{0.463} \tag{3}$$

where:

T_d – detention time (h), i.e., the time difference between the centroids of the inflow and outflow hydrographs.

Uncertainty in sediment routing model due to use of rating curves

The routing model introduced above requires series of continuous discharge observations to compute flow and sediment routing at the pond outlet. Yet this observed discharge is usually not measured directly in the stream but must be computed from another variable – water stage – which is favourable for measuring in field conditions at a high frequency (Sikorska *et al.* 2013; Le Coz *et al.* 2014). Hence, relationships between the desired discharge and the measured stage must be established for both the inlet and outlet of the pond by means of RCs. The rating curve most commonly used in hydrology has a power law form:

$$Q_i = a(H_i - b)^c \tag{4}$$

where:

Q_i – discharge ($m^3 \cdot s^{-1}$),
H_i – water stage (cm),
b – water stage at which discharge is equal to zero (cm),
a & c – coefficient & exponent of the rating curve (-).

Rating curves in such a form are usually used without considering any error in estimates of Q_i (Sikorska *et al.* 2013). Yet the effect of using these rating curves to obtain continuous observations of discharges may have huge consequences for the calibration and simulations with the (sediment) routing model. This effect is usually not considered, assuming implicitly that the discharge was measured directly in the field. Neglecting this fact will usually lead to biased estimates that rely on the discharge, which justifies the need to account for this type of uncertainty in simulations with routing-based models. Other uncertainty sources in the routing model (i.e., parameter, model structure, or the reservoir's capacity curve) are not considered here. This allows us to focus entirely on the effect of using such uncertain rating curves on the sediment routing model estimates.

Assessment of the rating curve uncertainty using a Bayesian approach

To assess the uncertainty of rating curves, we use a Bayesian approach that relies on Bayes' theorem (Gelman *et al.* 2013). Hence, the prior information on the rating curve parameters, $p(\theta)$, (elicited without any calibration data) is updated to the posterior, $p(\theta/Q_i)$, using information contained in discharge-stage pairs directly measured:

$$p(\theta|Q_i) = \frac{p(\theta)p(Q_i|\theta)}{\int p(\theta)p(Q_i|\theta)d\theta} \quad (5)$$

where θ represents all parameters (rating curve and its error) and $p(Q_i|\theta)$ is the likelihood function. This updating is done by taking Monte Carlo samples directly from the posterior. For inference, we use a likelihood function that combines the Box-Cox transformation with a bias model description implemented in a way similar to that of Sikorska *et al.* (2015), which allows us to also account, apart from parametric errors, for systematic and random errors in rating curve estimates. Such a systematic term has two parameters: σ – standard deviation, and τ – correlation length. The random component represents the uncertainty due to measurement error of discharge-stage pairs and it is assumed to follow a normal distribution with a mean equal to zero and a standard deviation ψ. The rating curve considering these two uncertainty components takes the form of:

$$Q_i = a(H_i - b)^c + B_i(\sigma, \tau) + e_i(\psi) \quad (6)$$

where, Q_i and H_i are discharge-stage pairs, and B_i and e_i are systematic and random errors of the rating curve corresponding to this pair.

This method is suitable for estimating rating curves that can be represented with power law functions (single or multiple compartments). As an output, uncertainty intervals on rating curve estimates can be derived. Here we use the 90% prediction intervals (composed of 95% and 5% percentiles) to describe uncertainty in rating curve estimates. These uncertainty estimates are then used for deriving uncertain discharges (storm hydrographs) at the inlet and outlet from the pond.

Scenarios: considering rating curve uncertainties in stormflow and sediment routing

We consider here the following scenarios which vary as to how information on rating curve uncertainty estimates is included into the routing model (see also Table 1):

- Scenario v5 – best RC_{in_mode} and best RC_{out_mode} – corresponds to the best estimates of both rating curves at the inlet and outlet, i.e., without considering any uncertainty in RCs (scheme 0),
- Scenarios v4 and v6 represent the situation when only uncertainty in the outlet RC is considered (scheme b),

Table 1 | Scenarios for considering rating curve uncertainties at the pond inlet and outlet

No	Scenario	Scheme	Inflow hydrograph acc. to:	Flow and SS routing acc. to:
1	v1	c	$RC_{in\_5\%}$	$RC_{out\_5\%}$
2	v2	a		RC_{out_mode}
3	v3	c		$RC_{out\_95\%}$
4	v4	b	RC_{in_mode}	$RC_{out\_5\%}$
5	v5	0		RC_{out_mode}
6	v6	b		$RC_{out\_95\%}$
7	v7	c	$RC_{in\_95\%}$	$RC_{out\_5\%}$
8	v8	a		RC_{out_mode}
9	v9	c		$RC_{out\_95\%}$

- Scenarios v2 and v8 cover the situation when only uncertainty in the inlet RC is considered (scheme a), as opposed to scenarios v4 and v6 (scheme b),
- The remaining scenarios (v1, v3, v7, v9) together represent the situation when uncertainty is considered in both the inlet and outlet RCs (scheme c).

Note that due to the routing through the pond, three scenarios of considering the RC uncertainty at the inlet to the pond multiply to nine different scenarios of the RC uncertainty at the pond outlet.

Metrics for assessing rating curve uncertainty contribution in sediment estimates

To quantify the impact of using such uncertain rating curves within different scenarios on the pond routing, we selected the following metrics:

- maximum outflow discharge; which is crucial for assessing the reservoir impact on flood reduction, or estimation of flood risk zones, and is also used for designing hydraulic structures,
- detention time; which reflects the average residence time of the flood wave in the reservoir and is directly used for estimating the model parameter,
- suspended sediment decay coefficient; which describes the intensity of reservoir sedimentation and enables calculation of sediment graph routing,
- maximum concentration of effluent suspended sediment; which is often mentioned in water quality standards as an indicator of the water (here outflow) quality,
- outflowing load of suspended sediment; which, in comparison with the inflowing load, illustrates the amount of the sediment yield captured in the reservoir.

RESULTS FROM THE METHOD APPLICATION TO A SMALL DETENTION POND IN WARSAW

Uncertainty of discharge rating curves at the pond inlet and outlet

Estimated posterior RC parameters are presented as histograms in Figure 2, while corresponding posterior rating curves at the pond inlet and outlet are illustrated in Figure 3. As seen from the latter figure, both rating curves were relatively well defined for both profiles until the stage of 160 cm that corresponds to the discharge of $5.8\,\mathrm{m^3 \cdot s^{-1}}$ and $4.8\,\mathrm{m^3 \cdot s^{-1}}$ for the inlet and outlet from the pond respectively. The application of rating curves outside this range is linked with higher uncertainty attached to discharge estimates and should be carried out with caution.

Measured rainfall-runoff-sediment events

For further investigations, five rainfall-runoff-sediment events measured in the period 2015–2016 have been selected (Table 2). Based on collected water stages and sediment samples, discharges and sediment concentrations were determined for upstream and downstream gauging stations. Please note that none of the recorded events was higher than the estimated applicability ranges of the rating curves ($>5.9\,\mathrm{m^3 \cdot s^{-1}}$ for the inlet and $>4.8\,\mathrm{m^3 \cdot s^{-1}}$ for the outlet from the pond). The average maximum inflow in the case of not considering any uncertainty in RC was estimated at $0.9\,\mathrm{m^3 \cdot s^{-1}}$. Using the 90% uncertainty interval ($RC_{in\_5\%}$ and $RC_{in\_95\%}$) resulted in a significant change in the analysed discharge between the best estimate, i.e., when no uncertainty is considered, and when the discharge estimates with uncertainty are considered. The upper and the lower bound of the estimated discharge were of a magnitude of, 59.8% lower and 78.1% higher on average, than the best estimate, respectively. The amount of inflowing sediment exceeded the effluent amount, i.e., particles were efficiently removed from the stormflow. An example event for illustrating this effect of using different rating curves on the computation of the inlet hydrograph is presented in Figure 4 for the event of 18.11.2015.

Effect of the pond routing with uncertain rating curves – characteristics of modelled events

Equations (1) and (2) were solved for nine defined scenarios. As a result, for each event nine hydrograph and sediment graphs were obtained at the pond outlet. An example of model application is presented for the modelled outflow discharge and outflow suspended sediment in Figures 5 and 6, respectively, while Table 3 summarizes results

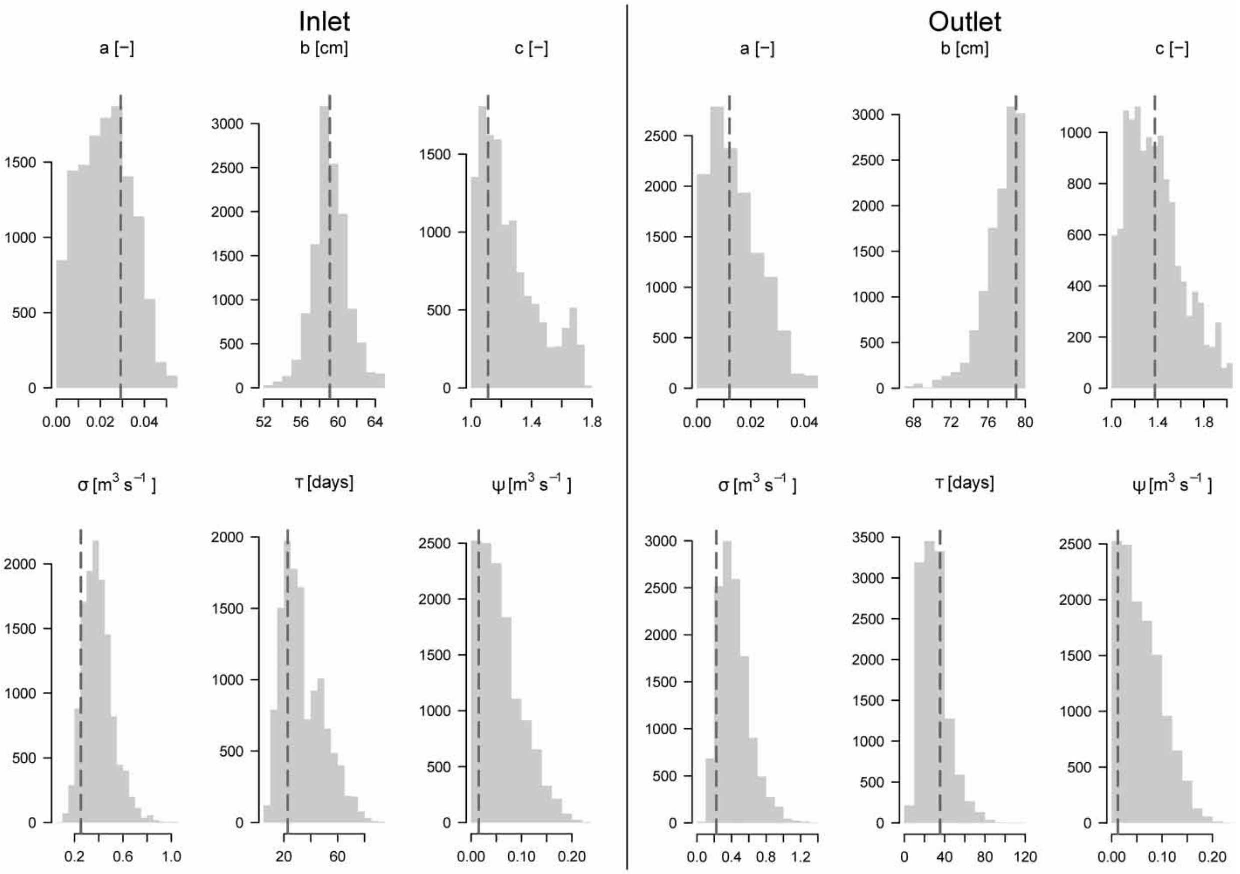

Figure 2 | Histograms of the posterior parameters of the rating curves at the inlet and outlet of the pond. The vertical dashed lines indicate the posterior mode (best estimate). The x-axes present values of estimated parameters: (a–c) are parameters of the rating curve, σ is the standard deviation of the systematic rating curve error, τ is its characteristic autocorrelation time, and ψ is the random error of the rating curve.

obtained for all five events for the mode (v5) and both most extreme scenarios (v1, v9). As long as the inflow was established by the same rating curve, outflow hydrograph and sediment graphs were simulated as similar to each other (regardless of the outlet rating curve used). This finding indicates that the change of the inlet rating curve has a higher impact on the pond outflow than the change in outflow curve. For the event of 18.11.2015 (Figures 5 and 6): the maximum discharge rose by 0.42% and 77.7% for scenarios v6 and v9 in comparison to v5, respectively, and dropped by 1.15% and 58.9% for scenarios v4 and v1. Consequently, the modelled maximum particle concentration varied from 13.7 mg·dm^{-3} up to 60.7 mg·dm^{-3}, which is a lot, and the amount of outflowing suspended sediment loads decreased for v1, v4, and v7, but increased for v3, v6 and v9.

DISCUSSION

In this work we assess the effect of uncertain discharge rating curves on the sediment routing through a small detention pond. The outflow from the reservoir was calculated according to nine scenarios varying in the information on the uncertain discharge rating curves, which simplifies to four schemes of accounting for RC uncertainties: (a) only uncertainty in the inlet rating curve, (b) only uncertainty in the outlet rating curve, (c) uncertainties in both inlet and outlet rating curves, and (0) neither uncertainty in the inlet RC nor in the outlet RC.

Our results from the small detention pond in Warsaw showed that neglecting any uncertainty (scheme 0) may lead to a huge under- or overestimation of sediment estimates at the pond outlet. Considering uncertainty in

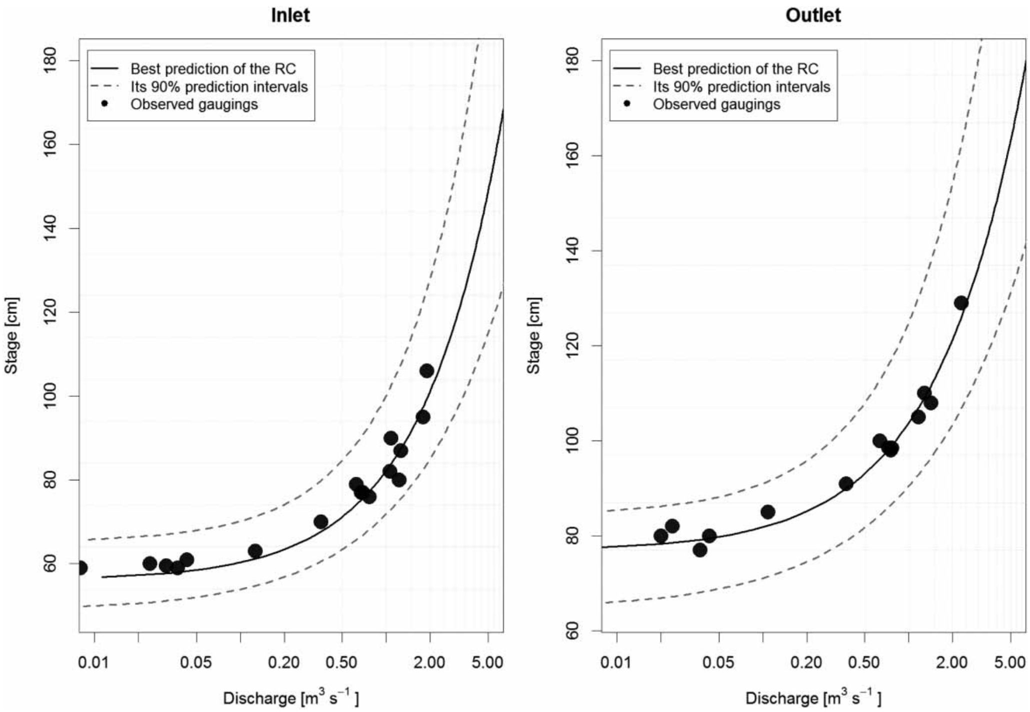

Figure 3 | Estimated uncertainty of discharge rating curves at the inlet and outlet from the pond. The solid black line describes the best estimates of the rating curves (mode), while dashed lines represent the 90% prediction intervals. Observed gaugings are plotted in dots.

the inlet rating curve (scheme a) had a much stronger impact on the sediment routing through the reservoir and led to higher uncertainty at the outlet than when only uncertainty in outlet rating curve was represented (scheme b). This could be explained by the fact that the form of the inlet rating curve strongly affects the shape of the inflow hydrograph and consequently the transport of the sediment load into the reservoir. Depending on which scenario for the inlet rating curve was used, different results could be obtained. Using the curve $RC_{in\_5\%}$ detained the outflow, prolonged the detention time, increased the sedimentation and therefore enhanced the trap efficiency of the reservoir. On the contrary, when the curve $RC_{in\_95\%}$ was used, it accelerated the outflow and consequently decreased the

Table 2 | Characteristics of the recorded five rainfall-runoff-sediment events according to three different forms of the inlet rating curve ($RC_{in\_5\%}$, RC_{in_mode}, and $RC_{in\_95\%}$) and the mode value for the outlet rating curve (RC_{out_mode})

No	Beginning date of the event	Total rainfall (mm)	Observed max. inflow $(m^3 \cdot s^{-1})$ acc. to			Observed max. outflow $(m^3 \cdot s^{-1})$ acc. to RC_{out_mode}	Observed max. SS concentration $(mg \cdot dm^{-3})$	
			$RC_{in\_5\%}$	RC_{in_mode}	$RC_{in\_95\%}$		in inflow	in outflow
1	4-Sep-2015	5.1	0.14	0.52	0.99	0.9	16.4	3.2
2	6-Sep-2015	19.0	0.58	1.25	2.17	1.23	58.4	17.8
3	26-Sep-2015	15.6	0.36	0.89	1.58	0.88	36.5	11.5
4	18-Nov-2015	10.9	0.42	0.99	1.75	0.98	208.3	61.7
5	20-Jun-2016	9.6	0.28	0.76	1.36	0.75	199.7	21.7
	Average	12.0	0.35	0.88	1.57	0.86	103.9	23.2

Note: SS, suspended sediment.

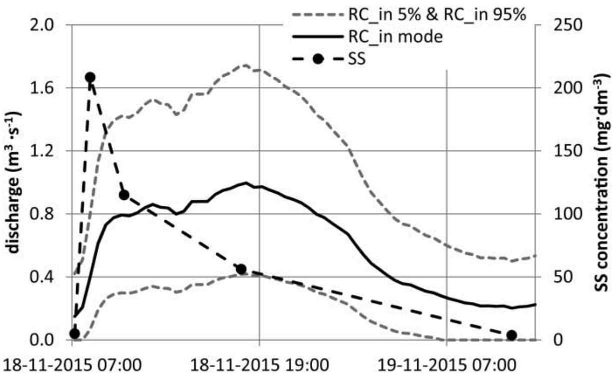

Figure 4 | Inflow discharge calculated according to the best estimate of the rating curve (RC_{in_mode}) and its 90% uncertainty interval ($RC_{in\_5\%}$ and $RC_{in\_95\%}$), and measured suspended sediment inflow to the Wyścigi Pond for one example event of 18.11.2015.

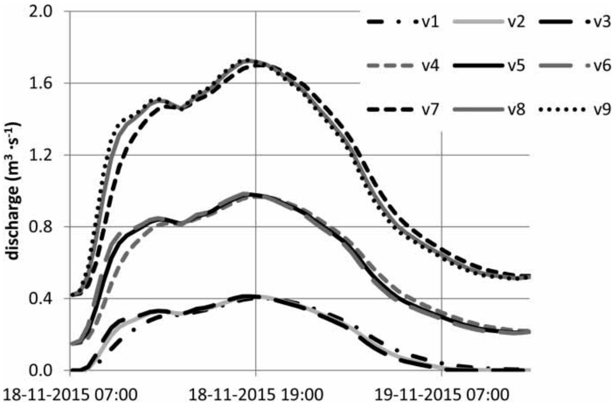

Figure 5 | Modelled outflow discharge from Wyścigi Pond according to nine scenarios for the same event of 18.11.2015.

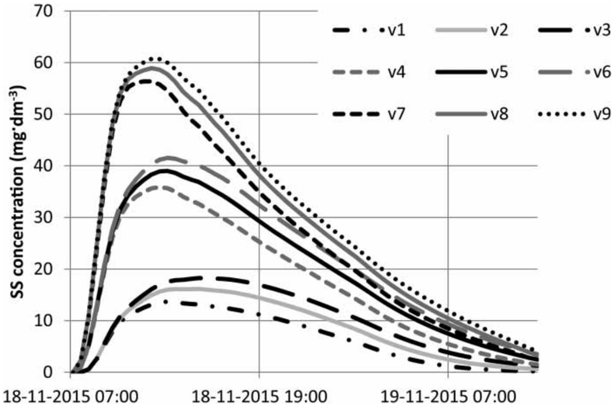

Figure 6 | Modelled outflow suspended sediment concentration from Wyścigi Pond according to nine scenarios for the example event of 18.11.2015.

Table 3 | Characteristics of simulated flood flows and suspended sediments at the outlet from the pond using uncertain rating curves

		Maximum outflow discharges ($m^3 \cdot s^{-1}$)			Detention time (h)			Suspended sediment decay coefficients (10^{-5} s^{-1})			Maximum sediment concentration in outflow ($mg \cdot dm^{-3}$)			Suspended sediment load in outflow (Mg)		
No	**date**	**v1**	**v5**	**v9**	**v1**	**v5**	**v9**	**v1**	**v5**	**v9**	**v1**	**v5**	**v9**	**v1**	**v5**	**v9**
1	4-Sep-2015	0.084	0.48	0.96	2.43	0.74	0.26	10.7	6.18	3.81	0.44	2.31	4.70	0.0004	0.019	0.089
2	6-Sep-2015	0.54	1.21	2.12	1.67	0.71	0.36	9.02	6.07	4.43	7.95	19.49	30.98	0.177	1.104	3.076
3	26-Sep-2015	0.30	0.85	1.54	1.86	0.62	0.30	9.48	5.70	4.07	3.35	10.42	17.29	0.032	0.293	0.871
4	18-Nov-2015	0.40	0.98	1.73	1.74	0.66	0.44	9.19	5.87	4.86	13.70	39.00	60.73	0.209	1.634	4.421
5	20-Jun-2016	0.26	0.75	1.36	1.95	0.68	0.32	9.69	5.95	4.20	6.69	22.04	37.94	0.050	0.581	1.830
	Average	0.32	0.85	1.54	1.93	0.68	0.33	9.62	5.95	4.27	6.43	18.65	30.33	0.09	0.73	2.06

deposition of sediments in the pond. Note however that these two curves should be analysed together as they describe the range of the uncertainty bands on the simulated sediment loads in the outflow from the reservoir.

In contrast, in the case of well-defined inflow, i.e., when RC_{in_mode} was used, meaning that no uncertainty was considered in the inlet curve, the form of the applied outlet rating curve ($RC_{out\_5\%}$, RC_{out_mode} or $RC_{out\_95\%}$) had rather a negligible influence on the simulated outflow. This issue may be further explained by the fact that the pond outflow relies on the outlet rating curve and additionally on the reservoir's volume curve. This volume curve was assumed to be constant for each scenario, which most likely led to mitigation of differences caused by the use of different outlet rating curves. Thus, it was also sensible that when both uncertain rating curves were used at the same time (scheme c), the observed effect was similar to that when only the inlet uncertain rating curve was considered. We expect similar effects in other reservoirs of similar properties (size, stream size, location). It has to be noted, however, that the quantitative results are case-specific and for other case studies would depend on the form and the accuracy of established rating curves, as well as on the reservoir design structure. Higher uncertainty values at both the reservoir inlet and outlet should be expected in the case of stations with complex rating curves such as with unstable river banks or out of bank flows, which increase significantly the uncertainty in rating curves (McMillan *et al.*, 2012). This was however never the case in our studied flood events. We thus recommend quantification of the exact effect of using uncertain rating curves for each case study independently, following the methodology developed here. Another important point is linked to other uncertainty sources that may contribute to the total uncertainty in sediment estimates in the outlet from the pond, and the way the uncertainty of rating curves is propagated through the model. Namely, as we focused purely on the effect of the rating curve uncertainty on the sediment routed through the model, other uncertainty sources were not explicitly considered. One has to be aware, however, that the routing model itself and its parameter are not error free, as well as input data – measured water stages. Regarding the latter, however, it has been shown that the uncertainty in water stages can generally be assumed to be at the level of 1–2 cm and thus are negligibly small (World Meteorological Organisation [WMO] 2008; Sikorska *et al.* 2013). Considering the parameter uncertainty, as the model has only one parameter it can be well identified from the data (Krajewski *et al.* 2017b). Thus, it is the structural uncertainty rather than the parameter uncertainty which may additionally contribute to the output uncertainty in sediments routed through the reservoir. This uncertainty may be significant, especially for one-dimensional sediment transport models (Ruark *et al.* 2011). The model structural error may also contribute to the non-linear propagation of the rating curve uncertainty through the routing model. Regardless of the above considerations, as our investigations have demonstrated, the estimates of discharges and sediment fluxes varied widely depending on how the uncertainty of the rating curve was incorporated into the modelling. However, the impact of the uncertain outlet curve was negligible for the routing concept in comparison to the effect of the inlet curve. Thus, the major source of errors was, in our case, the model input, e.g., the hydrograph estimated based on recorded water stages and the inlet rating curve. Based on our results we recommend that more efforts should be made to reduce the uncertainty in the inlet rating curve rather than the outlet rating curve. The inlet rating curve has to be constructed with the help of the maximum possible number of measurements, conducted at low, medium and high water stages, and needs to be regularly updated. The user of the routing model should keep in mind that poorly estimated rating curve(s) may lead to serious errors and biased conclusions, and might lead to wrongly designed retention reservoirs which do not fulfil their purpose or become silted at a much higher pace than expected. This is especially important not only for computing the sediment amount in the outflow from the reservoir but also for the calculation of the detention time of sediments within the reservoir. The consequences of not representing the uncertainty in model simulations will be underestimation of sediment loads in the reservoir outlet and overestimation of the sediment detention time, both leading to a higher risk of flooding and to higher sediment loads downstream than expected.

Alternatively, rainfall-runoff-sediment transport models (e.g., based on the washed-off concept (Sikorska *et al.* 2015)) could be used to calculate continuous discharge series at the reservoir inlet without the need to use the inlet rating curve. Use of such a model type would however introduce another source of uncertainty into the calculation of sediments at the pond outlet, which needs to be first quantified. Therefore, we would recommend using the inlet rating curve if enough information is available to quantify its uncertainty, and to quantify its effect on the simulation of sediments using the method proposed in this study.

CONCLUSIONS

In this paper, we proposed a feasible method for implementing and quantifying the uncertainty of discharge rating curves in the sediment routing model. This allowed us to assess the impact of using such uncertain rating curves on stormflow and suspended sediment routing through a small detention pond. Based on the presented study, the following conclusions have been drawn:

- A feasible method to account for rating curve uncertainty in sediment routing models has been proposed and tested for a small urbanized catchment and detention pond;
- Four different schemes, varying in how the information on the rating curves' uncertainty is considered in the routing model, were tested, to assess the impact of using uncertain rating curves on the simulated sediments in the reservoir outflow;
- Our results revealed, first, that substantial uncertainty is attached to the sediment estimates at the pond outlet which results from uncertain discharge rating curves. Second, the uncertainty in the inlet rating curve plays a more significant role for accurate estimates of sediments in the reservoir outlet, whereas the uncertainty in the outlet rating curve is of less importance.
- Our results also demonstrated that completely neglecting the rating curve uncertainty in sediment estimates leads to underestimation of sediment loads in the reservoir outlet and overestimation of the sediment detention time. This may have serious consequences in terms of a much faster pace of reservoir silting than designed and in higher than expected environmental impacts at downstream locations.

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