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RESEARCH ARTICLE

The mismatch between long-term monitoring data and modelling of solids wash-off to gully pots

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ABSTRACT

Urban runoff remobilises solids and their associated pollutants from urban-built environments and transports them to drainage systems via gully pots. This study presents an extensive monitoring campaign on the solids loading to drainage systems, including 104 gully pots as sampling locations and lasting 2 years. The solids loading is modelled with Build-Up and Wash-Off (BUWO) models and a Regression Tree (RT). The performance of the RT is substantially better than the performance of the BUWO models, such that it is not recommended to use a single BUWO model to predict the loading of a set of gully pots/catchments. It is discussed whether the generally observed mismatch between monitoring data and wash-off models, both in this study and in literature, points to a fundamental misunderstanding of the underlying processes. Finally, the results show that an increased street sweeping frequency does not significantly reduce the solids loading to drainage systems.

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Wash-off; field data; gully pot; catch basin; urban drainage; street sweeping

1. Introduction

1.1. Solids and drainage systems

Urban runoff is usually discharged from urban-built environments via drainage systems. Runoff contains solids and associated pollutants (see e.g. Sartor and Boyd 1972; Fulcher 1994; Herngren 2005), which could negatively affect the environment when discharged from the drainage system. The concentration of solids can be monitored or modelled to evaluate whether the environmental regulations are met or whether additional measures have to be taken to reduce the environmental impact of discharges from drainage systems (e.g. Athayde et al. 1983; Fletcher, Andrieu, and Hamel 2013; Cai et al. 2014; Alam et al. 2018; Todeschini, Papiri, and Ciaponi 2018). Moreover, the solids can settle in the drainage pipes (e.g. Crabtree 1989; Ashley et al. 1992; Van Bijnen et al. 2018), and consequently reduce maintain the hydraulic capacity of the drainage pipes. Gully pots can be regarded as a measure to reduce the solids loading to downstream urban drainage systems, while they are designed both to convey runoff from (paved) urban surfaces to the drainage system and to retain suspended solids.

1.2. Build-up and wash-off models

Build-up and wash-off (BUWO) models are used to predict the solids loading to drainage systems and describe the solids build-up on the street and the wash-off to the drainage system by rain. Some of these models are implemented in urban hydrodynamic models (such as SWMM, Infoworks ICM, and MIKE URBAN) and are applied both to large catchments (e.g. Bonhomme and Petrucci 2017) and small-scale lab setups (e.g. Naves et al. 2020). In this study, they are applied at regular gully pot catchments (order of magnitude 100 m^2). The models contain physical parameters such as the rainfall intensity and the antecedent dry weather period, and some calibration parameters that are not unambiguously linked to physical quantities or processes.

A classical BUWO model (according to Bonhomme and Petrucci 2017), involving four calibration parameters, assumes that the wash-off is a source limited process and is non-linearly dependent on the runoff. The build-up occurs during the dry weather period and grows exponentially to a maximum (as, for example, observed by Chow, Yusop, and Abustan 2015).

$$\frac{dM}{dt} = k_B(B_{max} - M_0) \cdot e^{k_B t_{ADWP}}, \;\; if \;\; R_i(t) = 0 \tag{1}$$

$$\frac{dM}{dt} = k_W \cdot Q(t)^{N_W} M(t), \;\; if \;\; R_i(t) \neq 0 \tag{2}$$

In which M (in kg/m^2) is the solid load on the street, k_B (in day^{-1}) the growth parameter of the build-up, B_{max} (in kg/m^2) the parameter representing the maximum possible load on the street, M_0 (in kg/m^2) the residual mass after the last rain event, t_{ADWP} the time (in days) of the antecedent dry weather period, R_i (in mm/hour) the rain intensity, k_W the wash-off rate parameter, Q (in mm/hour) the runoff, N_W the wash-off exponent. If the delay of runoff due to overland flow is set to zero (which is acceptable for the small gully pot catchments):

$$Q(t) = R_i(t) \tag{3}$$

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Several studies question the benefit of relatively complex models over simpler formulations (Charbeneau and Barrett 1998; Freni, Mannina, and Viviani 2009; Shaw, Stedinger, and Walter 2010). Therefore, a second model is evaluated in this study with only two parameters, which models the build-up as a linear process (similarly to, e.g. Barbé, Cruise, and Mo 1996; Morgan et al. 2017) and the wash-off as an exponential process. In this study, it will be referred to as the 'simple model' to distinguish it from the 'classical model'.

$$\frac{dM}{dt} = k_B - k_W \cdot R_i(t) \cdot M(t) \tag{4}$$

Although BUWO models are widely applied, the outcome of model validation is often unsatisfactory. Bonhomme and Petrucci (2017) reported several reasons, which can be found in literature, that could explain these unsatisfactory results:

- The BUWO process is not well described: studying the process at small scale should be performed to improve the models (e.g. Wijesiri et al. 2015).
- The calibration data: calibrating the models on data measured at the outlet of an urban catchment (which is common practice) is impossible (e.g. Gaume, Villeneuve, and Desbordes 1998), due to lack of variability or large uncertainty in the data.
- Scaling issues: the models are derived at small scale (order m^2) and applied at catchment scale (order ha) which is not comparable due to, for example, heterogeneous land-use at the catchment scale. The same holds for the time scale. Calibrating a model for a single rainfall event is possible, but a series of events is challenging, since each rainfall event requires its own calibration parameters (e.g. Naves et al. 2020).

The shortcomings of the current models are also highlighted by Bonhomme and Petrucci (2017), who measured the solid concentration at the outfall over a period of 11 months and calibrated the model represented by Equations (1) and (2) with the measurement data. The calibration parameters were highly variable with time, which led to the conclusion that parameters 'can hardly represent some physical characteristics of the catchment, and even if this was the case, these characteristics would be so variable that they would have a little practical interest for modelling'. This suggests that the model, although physically based at small scale, is performing as a black-box model at catchment-scale. These problems are further addressed in the discussion section.

1.3. Study objectives

This article presents the results of a measurement campaign on the solids loading to gully pots and has the following objectives

(1) To determine what parameters influence the solids loading to drainage system via gully pots.

(2) To determine whether the solids loading can be reduced by street sweeping.

(3) To determine whether the solids loading can be effectively modelled by BUWO models or an RT.

When resolved, some of the problems of BUWO modelling listed in section 1.2 can be assessed by:

- Determining with a Regression Tree (RT) whether parameters that are not included in the BUWO models, such as the season and the temperature, but are likely to contribute significantly (Rietveld, Clemens, and Langeveld 2021), should be included in BUWO models.
- Measuring the solids loading to gully pots instead of from the outfall of a drainage system, which excludes all the processes (e.g. sedimentation, erosion) within the gully pots and in the downstream drainage pipes.

1.4. Build-up and wash-off processes

Solids on streets originate from various sources, such as: local traffic (Wada, Miura, and Muraoka 1996; Barrett et al. 1998; Deletic, Ashley, and Rest 2000; Simperler, Keckeis, and Ertl 2019), atmosphere (Galloway et al. 1982; Sabin et al. 2006), construction activities (Broeker 1984; Ashley and Crabtree 1992), weathering of buildings (Jartun et al. 2008), animal wastes (Brinkmann 1985), trash (Brinkmann 1985), de-icing materials (Brinkmann 1985; Simperler, Keckeis, and Ertl 2019), and vegetation (James and Shivalingaiah 1985; Welker, Gelhardt, and Dierschke 2019).

The measured or modelled net result of the wash-off is the integral of a range of processes and is usually modelled by BUWO models holding only a few model parameters. In this study, the effects of two time-dependent climatological parameters on the solids loading are evaluated in more detail, namely the season and the temperature. Over the seasons, the availability of organic material on the street surface varies and consequently the solids loading in the gully pot varies as well (e.g. Pratt and Adams 1984; Ellis and Harrop 1984; Rietveld, Clemens, and Langeveld 2020). The temperature might affect the erodibility of solids as suggested by Rietveld, Clemens, and Langeveld (2021). Next to the season and the temperature, the effect of street sweeping is evaluated in this study. Street sweeping is applied in most urban areas for aesthetic and hygienic purposes, but it is also regarded as a water quality measure (e.g. Hixon and Dymond 2018).

The effect on the solids loading to drainage systems is under debate in literature. Street sweeping is more effective for gross solids than small solids (e.g. Walker, Wong, and Wootton 1999; Pitt et al. 2005; Amato et al. 2010). Sartor and Boyd (1972) found that street sweeping can remove up to 80% of particles >2 mm under test conditions (i.e. by sweeping more frequently than the occurrence of rainfall events and effective use of parking restrictions). Bender and Terstriep (1984) found that the average street load reduced by 50% by increasing the sweeping frequency from 0 to 3 times a week, while Pitt (1979) concluded that typical street cleaning programs (once or twice a month) removed <5% of the total solids. Bender and Terstriep (1984) concluded that the street cleaning operations tested would improve the runoff quality by a maximum of 10%. The statistical analysis also showed that frequent rains were probably more effective than street sweeping in keeping the streets clean.

Therefore, the efficiency of street sweeping to reduce the solids loading to the drainage system is questioned. Walker, Wong, and Wootton (1999) concluded that the benefits of increasing the frequency of street sweeping, beyond what is required to meet aesthetic criteria, are expected to be small in relation to water quality improvements. Grottker (1987) even concluded that in some cases the reservoir of free solids on streets increases by street sweeping. The brushes release part of the fixed load, which is not entirely removed by the vacuum cleaner of the street sweeper vehicles. Street sweeping is probably effective in removing gross pollutants, while it has an adverse impact on finer materials by making them readily available for wash-off by the next storm event (Vaze and Chiew 2002).

The solids present on the street are washed off during rain events. Wash-off models often use the rain intensity to model the wash-off rate. In the case, the solids loading of an entire rainstorm or several rainstorms is evaluated, the rain volume or event duration are sometimes taken into account (e.g. Ellis and Harrop 1984; Pratt and Adams 1984). Shivalingaiah and James (1984) and Gnecco et al. (2005) concluded that the maximum rain intensity is the parameter that is correlated strongest to the wash-off on the scale of a single rainfall event.

2. Materials and methods

The monitoring area for the solids loading to the drainage system is described in section 2.1, while the experimental setup is described in section 2.2. The calculation of the solids loading is described in section 2.3 and the data collection of the parameters influencing the solids loading is described in section 2.4. Section 2.5 contains the modelling procedure.

2.1. Monitoring area

A total of 104 gully pots were selected in a relatively new residential area (construction started in 2000), named Nesselande located in the Northeast of the city of Rotterdam (Figure 1(b)), which is the second-largest city in The Netherlands (based on population). It has a maritime climate with cool summers and moderate winters and an average rainfall of 870 mm/year during the monitoring campaign. Half of the monitoring area was also used in the study of Rietveld, Clemens, and Langeveld (2021). The area is homogeneous in terms of land-use offering the opportunity to split it into two similar parts for comparisons. The area and the gully pot

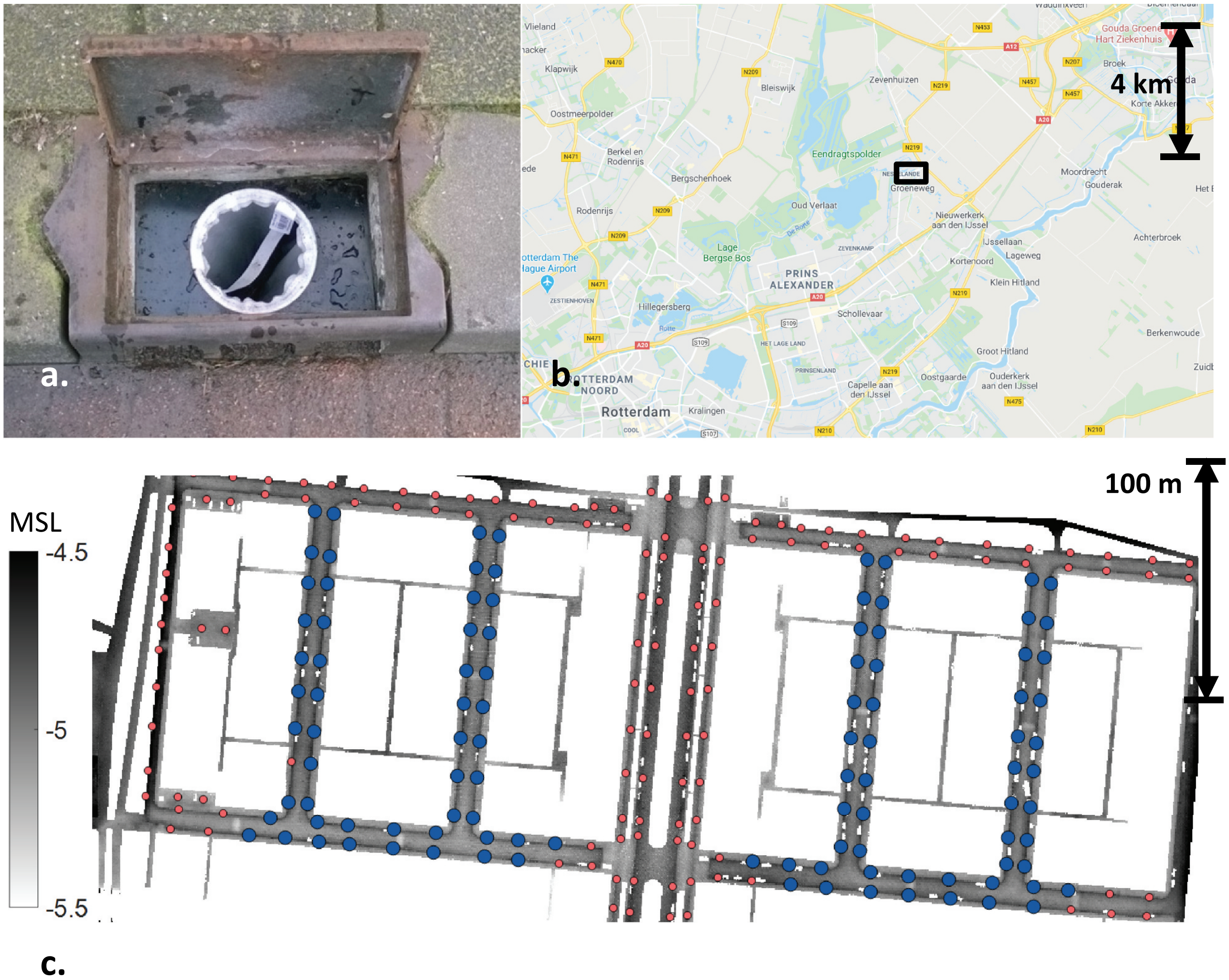

Figure 1. (a). A nylon filter is installed in the gully pot to collect the solids flowing into the gully pot. (b). Map with rectangle indicating the monitoring area. (c). Altitude street map of the monitoring area in which the blue dots indicate the selected gully pots and the red ones the not selected gully pots.

locations are shown in Figure 1(c), in which the blue dots indicate the selected gully pots and the red ones the not selected gully pots.

2.2 Experimental setup

The experimental setup was the same as used by Rietveld, Clemens, and Langeveld (2021) and consists of a nylon filter and a metal plate (Figure 1(a)). This metal plate is installed in a gully pot and sealed off around the gully pot wall. The nylon filter (with a diameter of 18 cm and a length of 50 cm) is placed in the middle of the metal plate and filters the solids out of the runoff during rain events. A pore size of 50 µm was selected as a trade-off between two conflicting interests, namely a minimum pore size to keep the hydraulic capacity of the gully pot at sufficient level to avoid local flooding, and a maximum pore size to remove most solids from the runoff. A more thorough discussion of this choice can be found in Rietveld, Clemens, and Langeveld (2021).

The filters were emptied every ~3–4 weeks between April 2018 and April 2020, both to prevent clogging of the filters and to identify the time dependency of the solids loading. The filters (without excess water) were weighted and the (wet) masses were registered at the monitoring area.

2.3 Solids loading

The wet mass of the solids was registered for each gully pot at the monitoring location. Next to that, on each measurement day, samples were collected from four gully pots to determine the average wet content in the lab. The average dry content was multiplied by the wet mass to estimate the solids' dry mass of each gully pot. The solids loading to a gully pot ($kg \cdot day^{-1}$) is defined as:

$$L(i) = \frac{f_d \cdot m_w(i)}{\Delta t} \tag{5}$$

In which f_d is the average dry fraction, $m_w(i)$ the wet mass of filter i, and Δt the time measurement interval.

2.4 Parameters related to the solids loading

The solids loading to gully pots is influenced by the availability of solids on the street and the transport capacity of runoff. A Regression Tree (RT) is used to determine what factors related to these two processes contribute significantly to the solids loading. The BUWO models only use the factors 'gully pot catchment area' and 'rain intensity' and lump all other factors in calibration parameters. An overview of the evaluated parameters and their origin is provided in Table 1, the range and units of the variables are provided in Table S1 of the Supplementary Material.

2.4.1. Build-up parameters

The availability of solids per gully pot depends on the size of the gully pot catchment area, which is determined by the application of the eight-direction flow approach (Jenson and Domingue 1988) on a Digital Elevation Model (DEM) provided by the municipality of Rotterdam. This DEM is obtained by laser altimetry measurements in 2016 and has a spatial resolution of 0.5 × 0.5 m. Errors in this dataset caused by cars on the street have been filtered out by kriging.

The season influences the availability of solids on the streets by leaf fall from deciduous trees. Similar to Halverson et al. (1985), four seasons/tree phases are distinguished, namely leaf growth, full capacity, leaf abscission, and no leaves. The start and end dates of the tree phases depend highly on climate and weather and are based upon images of the streets and trees made during the measurements.

Rietveld, Clemens, and Langeveld (2021) suggested that the temperature might influence the erodibility of solids, since dry soil is more prone to erosion than wet soil, and the dryness is assumed to depend on the temperature. Therefore, the mean temperature during a monitoring period is used as a parameter and is assumed to be homogeneous in this relatively small monitoring area.

Street sweeping with sweeping vehicles was applied in the monitored area by the municipality, which also registered when it was applied. The sweeping frequency was adjusted (which is more extensively described in section 3.3) during the monitoring period upon the authors' request to observe its effect.

Table 1. Parameters evaluated by the RT.

Parameter	Calculation	Data source
Solids build-up variables		
Gully pot catchment area	The eight-direction flow approach (Jenson and Domingue 1988) to determine the size of the paved area connected to a gully pot	Digital elevation model based on laser altimetry measurement from 2016 owned by the municipality of Rotterdam
Tree phase	Classification	Visual observation and photos
Temperature	Mean air temperature during the measurement period.	Temperature measurement (at a temporal resolution of 5 minutes) by weather station Ommoord (at a distance of 4 km).
Street sweeping	Events per week during the measurement period.	Timesheets of the municipality
Antecedent dry period	The number of dry days before the measurement period, while a day is considered dry when the rainfall volume is less than 1 mm.	Rain radar KNMI
Solids wash-off variables		
Rainfall volume	Maximum rainfall intensity in 5-minute interval during the measurement period.	Rain radar KNMI
Rainfall intensity	Mean rainfall per day during the monitoring period.	Rain radar KNMI
Peak discharge	Maximum rain intensity multiplied by the connected area.	Rain radar KNMI and digital elevation data.
Water volume	Rain volume multiplied by the connected area.	Rain radar KNMI and digital elevation data.

The solids load on streets increases over time if they are not removed by, e.g. rain or street sweeping. Therefore, the length of the antecedent dry period is usually assumed to contribute positively to the solids loading to drainage systems (Sartor and Boyd 1972; Irish et al. 1995; Vaze and Chiew 2002; Chow, Yusop, and Abustan 2015; Morgan et al. 2017). In this study, a day is defined dry if the rainfall volume is less than 1 mm.

2.4.2. Wash-off parameters

The rainfall data used originate from the meteorological radar dataset of the Koninklijk Nederlands Meteorologisch Instituut (KNMI), which contains 5-minute interval rain volume measurements on a 1 km^2 grid. This relatively short time-interval is used, since the gully pot catchment area is small, which results in a short response time.

The 5-minute interval data is used in the BUWO models, while only the maximum rainfall intensity during a monitoring period is used in the RT, since an RT can only handle a single value. The maximum intensity was chosen, since it is the most important parameter for the wash-off during a rainfall event (Shivalingaiah and James 1984). The solids loading is studied on a timescale of a few weeks, so the wash-off rate is integrated over the time between two measurement days. Therefore, the wash-off in that period depends on the integral of the rainfall intensity as well, which is the rainfall volume.

The rainfall intensity affects the transport capacity and the erosion capacity by raindrop impact and the rainfall volume affects the total transport over an event. The street surface of the gully pot catchment might be more effectively cleaned when the volume of water flowing over the area is larger which is affected by the size of the area. Therefore, the parameters peak discharge and water volume are also evaluated in the RT.

2.5. Modelling

2.5.1. Regression tree analysis

Regression Trees (Breiman et al. 1984) are commonly used in data mining to explore the structure of datasets. It shows the structure of the data (in this study on the solids loading) by rules, which appear at each node and split the dataset into two subsets. In this study, the criterion for the best split is defined as the split predictor that minimizes the *p*-value of χ^2 tests of independence between each (pair of) explanatory variable(s) and the response variable. If all tests yield *p*-values larger than 0.05, or the subset is smaller than 60, splitting is stopped.

The procedure to obtain a single tree is based upon the procedure of De'ath and Fabricius (2000) and consists of 6 steps (and is also applied by Rietveld, Clemens, and Langeveld 2020):

1. Divide the data into n (usually a number between 5 and 10, in this study n = 5) random subsets of approximately equal size.
2. Cross-validate by dropping each subset in turn (test data) and build a tree using data from the remaining subsets (training data).
3. Predict the responses for the omitted subset, calculate the mean squared error for each subset and sum over all subsets.
4. Repeat steps (2)-(3) for a series of tree sizes.
5. Take the smallest tree (the pruned tree), such that the error is within one standard deviation of the minimum error of the cross-validation trees.
6. Repeat m times (in this study m = 50 resulted in a clear distribution) steps (1)–(5) and select the most frequently occurring tree size from the distribution of selected tree sizes and subsequently a common tree.

2.5.2. BUWO models

The solids loading obtained from the monitoring data as defined in Equation (6) is used to calibrate the BUWO models as represented in Equations (1)–(4). The solids loading from the models is calculated as following:

$$L_{model}(i) = \frac{A(i)}{\Delta t} \int_{t_{start}}^{t_{end}} \frac{dM_{wash-off}}{dt} dt \qquad (6)$$

In which L_{model} is the modelled solids loading, *A(i)* the paved surface area connected to gully pot *i*, and $M_{wash\text{-}off}$ the wash-off. The wash-off can be calculated by the change in the solids load on the street as represented by Equation (2) or the second term of Equation (4). The calibration parameters of the models are obtained by minimising the mean squared error.

3. Results

3.1. Data exploration

A total of 3046 measurements were performed over a period of approximately 2 years resulting in a mean dry mass per measurement of 185 g, but strongly varying between 0 and 4400 g. The latter and a number of other measurements (51 in total) resulted from filters containing an extraordinary amount of material, which could often be recognised at the monitoring area as concrete, wall plaster, or paint. In some cases, this divergent material could not visually be noticed, but the extraordinary high mass (which lower limit was set at three times the mean value of the corresponding monitoring period, which was chosen based upon the measurements) indicated illegally dumped material (76 in total). Both sets of observations were removed during the post-processing of the data to avoid wrong associations in the statistical analyses, since these materials are most likely manually dumped into the gully pots, instead of transported by the run-off process. This removal of outliers reduced the dataset to 2919 observations.

3.2. Regression tree

Table 2 contains the type of relation between the parameters and the solids loading to gully pots in the Regression Tree (RT). Parameters that correlate positively are indicated with a plus sign, whereas negative correlations with a minus sign. The RT with 15 terminal nodes is shown in Figure 2(a).

The rainfall intensity is the most important parameter in the RT. It represents the transport capacity and the erosion capacity by raindrop impact and is positively correlated with the solids loading. Shivalingaiah and James (1984) concluded that this parameter correlated strongest to the wash-off on the timescale of a single rainfall event, which is apparently also the case for a period of ~3–4 weeks with several rainfall events. The

Table 2. Type of relations between the parameters and the solids loading to gully pots and their relative importance (based on the reduction of the mean squared error). Positive correlations are indicated with a plus sign and negative correlations with a minus sign.

Parameter	Relation with solids loading	Relative importance
Catchment area	+	0.018
Leaf abscission	No relation	0
Leafless	No relation	0
Leaf growth	No relation	0
Full capacity	No relation	0
Temperature	+	0.102
Street sweeping	+	0.091
Antecedent dry period	No relation	0
Rainfall volume	+	0.135
Rainfall intensity	+	0.633
Discharge	+	0.005
Water volume	+	0.017

rainfall volume is also related to the transport capacity of solids. It is the second most important parameter in the RT and is also positively correlated with the solids loading.

Rietveld, Clemens, and Langeveld (2021) suggested that the temperature (as a proxy-parameter) might be correlated to the solids loading, since the temperature might be correlated with the wetness of soil and dry soil is more susceptible for erosion than dry soil. The RT confirms that the temperature is correlated with the solids loading to gully pots. Whether there is indeed a causal relation between the temperature, erodibility, and the solids loading could not be verified with the data. The parameters rain volume and rain intensity are represented in the BUWO models as presented in section 1.3. However, the temperature, which is the third most important parameter, is not.

The parameter catchment area, street sweeping, peak discharge, and water volume all contribute positively to the solids loading, but less strong than the parameters previously discussed. The contribution of the catchment area is small, but also contributes via the parameters peak discharge and water volume, since these are multiplications of the catchment area with, respectively, the rain intensity and the rain volume.

The performance of this RT could be represented by the Nash-Sutcliffe efficiency, which equals 0.57 for the randomly selected (as described in section 2.3.2.1) training set and 0.60 for the test set (usually the training set shows a higher Nash-Sutcliffe efficiency). These values are moderate, and it is concluded that the prediction of the solids loading to individual gully pot should not be made using this model. However, Figure 2(b) shows that the dynamics of the total loading to all gully pots are well captured by this RT and the Nash-Sutcliffe efficiency of this total loading equals 0.92.

3.3. Street sweeping

Street sweeping is expected to have long-term effect, since sweeping reduces the solids load on streets (e.g. Sartor and Boyd 1972; Bender and Terstriep 1984; Sutherland and Jelen 1997; Amato et al. 2010), which makes less solids available for the next storm events. Therefore, instead of looking at the effect of street sweeping in time slots of a few weeks (as done in the RT), the effect of street sweeping is analysed over a period of two times 5 months in this section.

The monitoring area was virtually split into two similar catchments (in terms of land-use). In the first 5-month period, the sweeping frequency was approximately similar in both catchments, while in the second 5-month period, the frequency differed substantially. The solids loading per unit area to all gully pots in these two catchments and two periods are compared:

$$LA_{catchment} = \frac{f_d \cdot \Sigma_i m_w(i)}{\Delta t \cdot \Sigma_i A(i)} = \frac{\Sigma_i L(i)}{\Sigma_i A(i)} \qquad (7)$$

In which LA (in kg·day^{-1}·ha^{-1}) is the solids loading per unit area, and $A(i)$ (in ha) the paved catchment area of gully pot i. Since the covariance between the parameters in negligible and the uncertainty in the measurement interval is negligible too, the uncertainty in LA is defined as:

$$u(LA) = \sqrt{\left(\frac{\Sigma_i m_w(i)}{\Delta t \cdot \Sigma A(i)} u(f_d)\right)^2 + \left(\frac{f_d}{\Delta t \cdot \Sigma A(i)} u(\Sigma_i m_w(i))\right)^2 + \left(\frac{f_d \cdot \Sigma_i m_w(i)}{\Delta t \cdot \Sigma A(i)^2} u(\Sigma_i A(i))\right)^2} \qquad (8)$$

In which the uncertainty (95% confidence interval) in fd is estimated at ±30%, which is estimated based on the observed variability of this parameter for different gully pots during the same measurement day. The uncertainty (95% confidence interval) in Σi(i) is determined by 2 times the standard error in the solids loading to the individual gully pots, and the uncertainty (95% confidence interval) in the catchment area is estimated at ±10%.

The impervious area ΣiA(i) is registered in the Basisregistratie Grootschalige Topografie [Register of Large-Scale Topography] of the Dutch government, which states that the uncertainty in the position of the objects in this register is ±0.2 m. Considering streets with a width of ~10 m, some impervious areas in front gardens (which is not part of the register) that could contribute to the runoff, and some permeable areas in front gardens that could handle some runoff from the streets, the uncertainty in the summed catchment area is estimated at ±10% (95% confidence interval).

Figure 3(a) shows that the solids loadings during these monitoring periods in the two catchments do not significantly differ. Therefore, in accordance with the findings of Walker, Wong, and Wootton (1999), it is concluded that increasing the sweeping frequency (in these catchments and at the evaluated frequencies) results in a negligible effect on the solids loading to gully pots. Bender and Terstriep (1984) concluded that the frequent rains in their study were probably also more effective in keeping the streets clean than street sweeping. Therefore, a significant reduction of the solids loading can only be expected when the street sweeping frequency is higher than the rain frequency.

Figure 3(b) shows the relation between the inter-sweeping-event time and the relative fraction of dry periods. The markers in the figure indicate the two applied street sweeping frequencies. The fraction of dry periods at these two points differs approximately 10%, which was apparently not enough to substantially influence the solids loading.

3.4. Build-up and wash-off model

In Equations (1)–(4) the 'classical' and 'simple' BUWO models are introduced. Additional parameters that could account for street sweeping are not included, since it is shown in

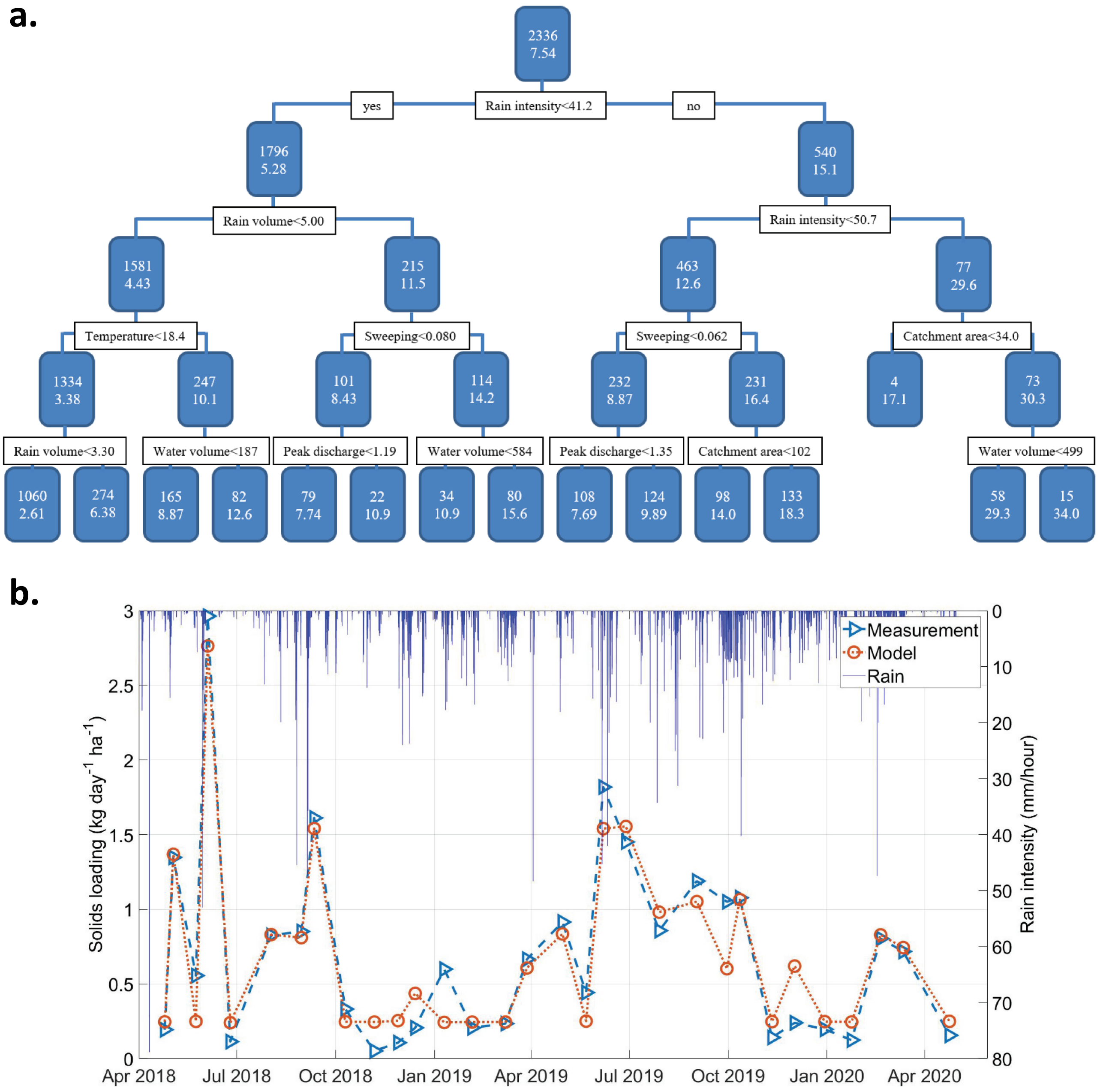

Figure 2. (a).The RT for the solids loading to gully pots. A step to the left is taken if the criterion is met and to the right if it is not met. The values at the nodes are the number of observations in the group and the mean solids loading of the group. Table S1 shows the ranges and the units of the variables. (b). Comparison between the total measured and modelled (by the RT) solids loading to all monitored gully pots over time.

the previous section that there is no significant effect. The models are calibrated using the observations of each individual gully pot. Both the simple and classical model have a very low Nash-Sutcliffe efficiency of, respectively, −0.053 and −0.0013, which indicates that the mean value represents the solids loading to individual gully pots equally well as the models. The performance of the models for the total solids loading (summation of the individual gully pots), as shown in Figure 4, is slightly better than for individual gully pots, with a Nash-Sutcliffe efficiency of 0.030 for the simple and 0.30 for the classical model.

In Table S2 of the supplementary material, a comparison is made between the values of the calibration parameters of the classical model found in this study and found in literature. The build-up parameters are comparable to values in literature, but the wash-off parameters are not. In some studies, N_W is a priori fixed to 1. If this is applied, the value for k_W becomes more comparable with the values reported in literature (but the Nash-Sutcliffe efficiency becomes even lower with −0.12 for individual gully pots and 0.19 for the total solids loading).

Instead of one model representing all gully pots, each gully pot could also be modelled with a separate model. This approach is followed to evaluate the sensitivity of the calibration parameters. Figure 5(a) shows the spread of the calibration parameters in this set of models. This spread is substantial, in particular in k_B and $k_{W,}$. Therefore, it is questionable whether the dominant processes are captured in this model. This notion is supported by Bonhomme and

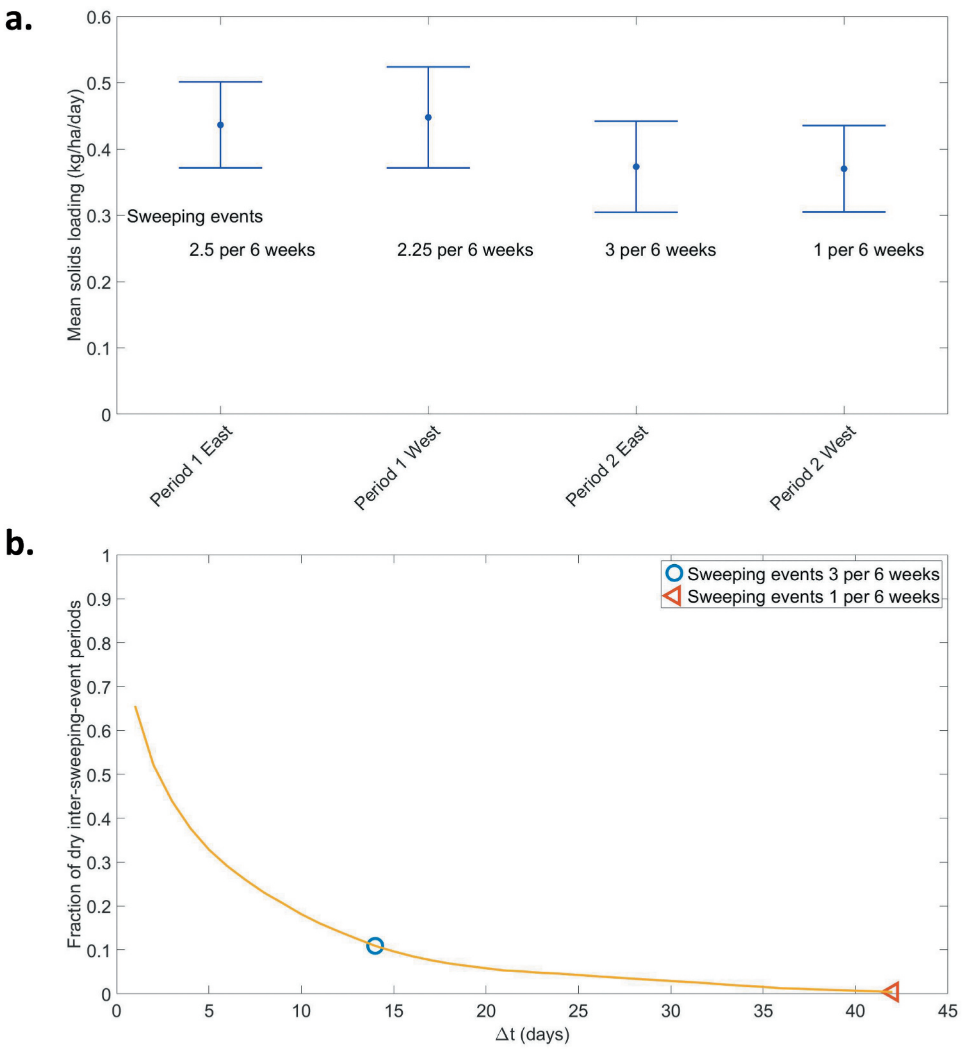

Figure 3. (a). Street sweeping frequency and the mean solids loading in the two monitoring periods and two catchments. The difference in street sweeping frequency does not significantly affect the solids loading. (b). The relation between the inter-sweeping-event time and the relative fraction of dry periods of these timeslots.

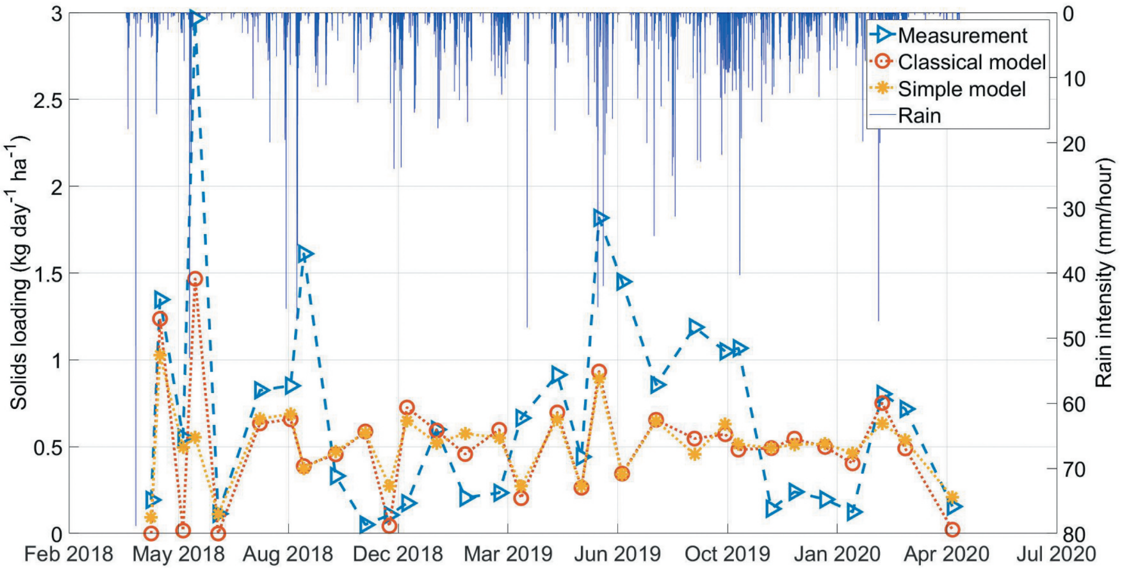

Figure 4. Comparison between the total measured and modelled solids loading to all monitored gully pots over time. Calibration parameters simple BUWO model: $k_B = 5.27{\cdot}10^{-2}$ g·m^{-2}·day^{-1} and $k_W = 7.01$ hour·day^{-1}·mm^{-1}. Calibration parameters classical BUWO model: $B_{max} = 4.45$ g·m^{-2}, $k_B = 1.38{\cdot}10^{-2}$ day^{-1}, $k_W = 9.03{\cdot}10^{-5}$, and $N_W = 6.14$.

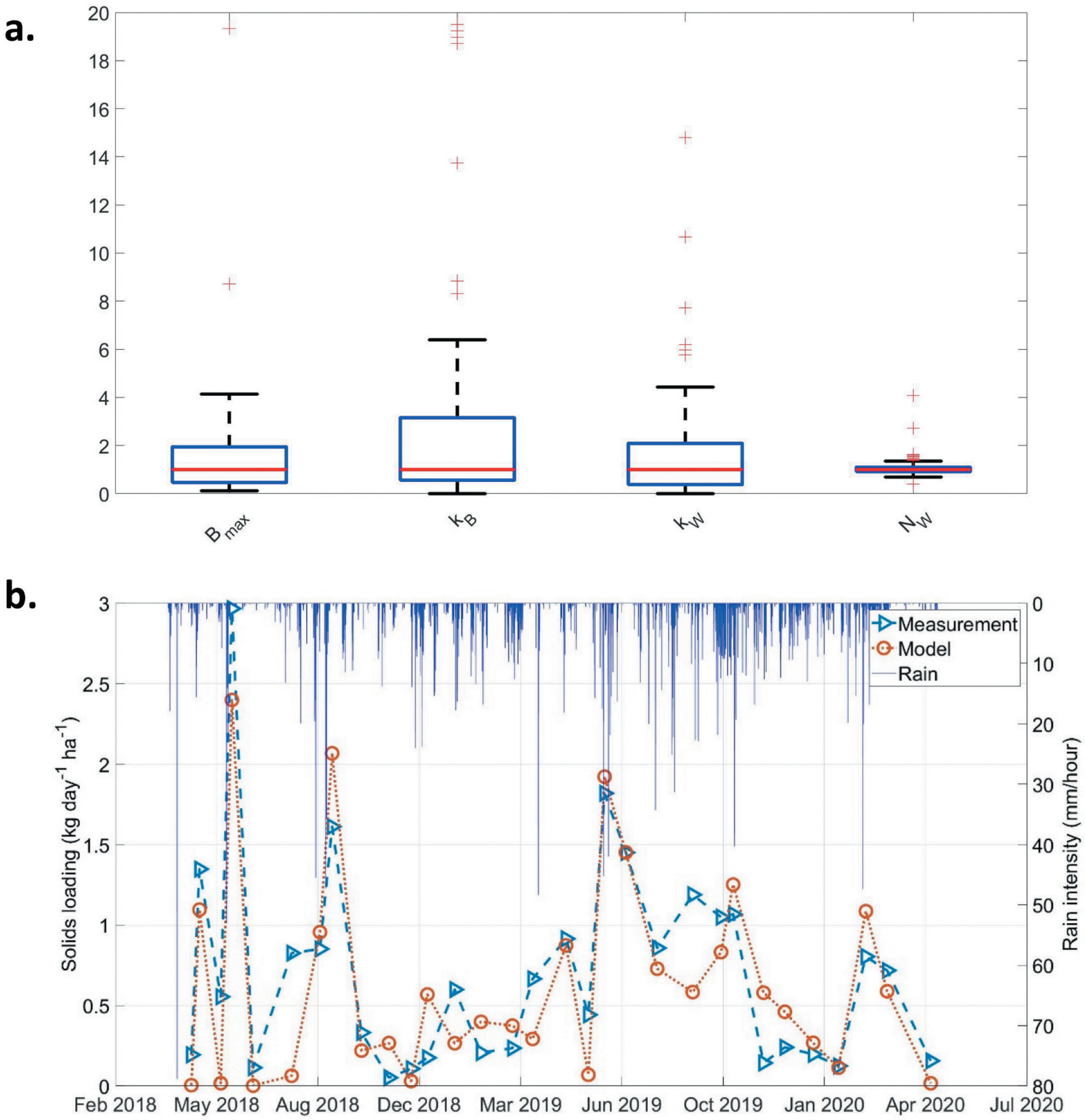

Figure 5. (a). The spread in the calibration parameters of the set of classical BUWO models is displayed in this boxplot by dividing them by their median values, which are: B_{max} = 5.29 g·m^{-2}, k_B = 1.45·10^{-1} day^{-1}, k_W = 0.577, and N_W = 2.36. (b). Comparison between the total measured and modelled (by the set of classical BUWO models) solids loading to all monitored gully pots over time.

Petrucci (2017) who found in their study that the calibration parameters showed a very limited portability, which led them to the conclusion that parameters 'can hardly represent some physical characteristics of the catchment, and even if this was the case, these characteristics would be so variable that they would have little practical interest for modelling'.

The performance of this set of classical models is obviously better than the application of a single classical model as in Figure 4. The Nash-Sutcliffe efficiency is 0.36 for the individual gully pots and 0.76 for the total solids loading to all gully pots, as shown in Figure 5(b).

4. Discussion

The Nash-Sutcliffe efficiencies of the two BUWO models evaluated in this study are approximately zero, indicating that the mean value of the observations explains the variation in the observations equally well as the models. The Nash-Sutcliffe efficiency slightly increases when the performance is evaluated for the summation of all gully pots, but is still relatively small. When a model is developed for each gully pot, the dynamics of the summed solids loading is pretty well described, as shown in Figure 5(b).

These results confirm the findings of Naves et al. (2020), who modelled the solids wash-off of predefined solids from an artificial street, based on the experiments of Naves et al. (2019). Despite the accurate definition of the (initial) conditions (such as the solids load on the street and the rainfall), for each tested situation, a wide range for the values of the calibration parameters was suitable when calibrating their physically based BUWO model. Individual tests could be represented relatively well with the model, however the portability of the values to other tests was virtually absent. It is concluded, supporting to Bonhomme and Petrucci

(2017), that the calibration parameters in the BUWO models can hardly be regarded as representing some physical characteristics of the catchment.

The performance of the RT is better than the BUWO models as indicated by the Nash-Sutcliffe efficiency of approximately 0.60 for the loading to individual gully pots and 0.95 for the summed loading to all gully pots. This suggests that a data-driven model produces better results than the semi-physical BUWO models. The evaluated data-driven model includes some parameters that are not included in the BUWO models, of which the temperature is found to be the most influential. The effect of this parameter on processes influencing the solids loading to gully pots should be studied in future research. It may have been overlooked in literature, as many studies do not span several years.

Nevertheless, it is questionable whether the addition of parameters is the only reason the RT performs better than the BUWO models. RTs allow local relations within subgroups of the data, which clarifies the effects of (a combined set of) parameters on the outcome variable. This property results in a very flexible type of modelling, resulting in a site-specific model, which implies that the identified relations are informative and could be valid in other areas, but the model itself cannot be applied in another area without proper calibration. Moreover, these types of models describe the dynamics, but do not reflect or contribute to a fundamental understanding of the processes involved. BUWO models, which seem to contain a more physical description of the processes, have neither proved to be portable, since either each gully pot catchment has to be modelled separately with a large range of calibration parameters, or the application of one model results in poor performance.

Despite decades of research into the wash-off and related processes (theoretical and experimental research) reported in literature (e.g. Sartor and Boyd 1972; Pitt 1979; Pratt and Adams 1984; Ellis and Harrop 1984; Pitt et al. 2005; Bonhomme and Petrucci 2017), hardly any generic conclusions can be drawn and at best site-specific statistical relations have been identified with an unknown validity beyond the monitoring period. This suggests that model calibration is required for each catchment, and on top of that the portability of calibrated parameters for one location to another rain event proves to be troublesome as well (Naves et al. 2020), indicating that the calibrated models are likely to be only able to 'now- and here cast'.

An option worth considering for further research is to investigate whether the processes influencing the solids loading to gully pots contain non-linear feedback which can, under certain conditions, initiate inherent unpredictable dynamic behaviour, also known as chaos (see e.g. Genesio and Tesi 1991). The suspicion on chaotic characteristics has been uttered for some of these or related processes

The wash-off process starts with rainfall, which is known to show chaotic behaviour in space and time (Rodriguez-Iturbe et al. 1989; Sivakumar 2000). The impact of the raindrops erodes solids from the surface, depending on the erodibility of the solids. This erodibility is influenced by the characteristics of the individual particle, the moisture content of the particles (as discussed in section 3.2), the way they are deposed on the surface, the cohesiveness of surrounding particles, the street surface, etc.

The rainfall-runoff process might also be a chaotic process (Sivakumar et al. 2001). The eroded solids can get transported by runoff over the (street) surface. This flow is strongly intermittent depending on the rainfall intensity, which influences the settling (which is chaotic in some conditions, Verjus et al. 2016) and erosion processes in this flow. These settling and erosion processes are to some extent comparable to coastal morphology, which might exhibit chaotic behaviour (Baas 2002).

These individual processes have to be studied in more detail and in relation to each other to conclude whether wash-off is a chaotic process and if so, under what circumstances. A first step could be to describe the individual processes in simple 1D mathematical models and search for non-linear feedback. If these are found, the impact of the individual processes on the overall wash-off can be evaluated. If the overall perspective proves to be inherently chaotic, it would imply that for all practical purposes a data-driven approach for a specific catchment is a better alternative when compared to using a BUWO model with parameters taken from literature. An example of such a data driven approach, which works satisfactorily, is provided in section 3.2. A similar approach could be used in other catchments.

5. Conclusion

The Regression Tree (RT) shows that the solids loading is most strongly influenced by the rain intensity, rain volume, and temperature. The rain intensity and rain volume are related to the erosion of solids from the street and the transport of solids over the street. The temperature might influence the erodibility of solids from the street.

The Build-Up and Wash-Off (BUWO) models generally show poor performance, in particular, when compared with the performance of the RT. Therefore, it is not recommended to use a single BUWO model, calibrated for a set of gully pots or catchments, to predict the solids loading to individual gully pots or catchments. If each gully pot or catchment is separately modelled by a BUWO model, the performance increases strongly. However, since this results in a large variation in the calibration parameters, it is questionable whether this set of models is a better description of the physical processes or whether the additional calibration parameters only act as fitting parameters. The latter would mean that the model acts as a black-box model and cannot be used in other catchments without a new calibration procedure including a large amount of data of the new catchment.

The results have shown that in the monitored area street sweeping cannot be regarded as a measure to decrease the solids loading to gully pots unless unrealistically high sweeping frequencies are applied. Therefore, the choice for a street sweeping frequency should rather be based on aesthetic/hygienic criteria than water quality criteria. Whether this conclusion can be generalised to other areas depends amongst others on the climatic conditions.

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