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RESEARCH ARTICLE

Selecting a series of storm events for a model-based assessment of combined sewer overflows

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ABSTRACT

The hydraulic verification of combined sewer systems as well as the assessment of combined sewer overflows (CSOs) can be conducted using a hydrodynamic model. Unfortunately, long-term simulations with hydrodynamic models for the assessment of CSOs can cause unacceptably long computation times. Using only a series of storm events instead of a precipitation continuum can reduce this time and enables parallel simulation of single storm events. We introduce a method to select this series of storm events. The method's parameters have been optimized to replicate the overflow volume of the continuous simulation and to minimize the overall computation time. This optimization revealed a generally applicable parameter set that results in series of storm events that are shorter than the precipitation continuum by 86.2–95.2% for the investigated cases. Additionally, the deviation of overflow volume between continuous simulation and series simulation ranges between only 0.1% and 4.1%.

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Storm events separation; stormwater management; urban drainage modeling

Introduction

Generally, combined sewer systems have to be verified (i) hydraulically and (ii) in terms of their compliance with standards for combined sewer overflows (CSOs). These verifications are implemented in various country-specific guidelines (see de Toffol 2006).

The hydraulic verification requires the calculation of water levels at every junction of interest, e.g. to determine the 'overflow frequency' (how often the hydraulic head is above ground level at single manholes). For this purpose, only simulation techniques using hydrodynamic models, solving the full de Saint-Venant equations, are applicable.

CSO structures are of environmental interest with respect to their qualitative and quantitative impacts on receiving water bodies. The assessment of CSOs requires estimating the overflow volume or frequency based on long-term simulations. In contrast to detailed hydrodynamic models used for the hydraulic verification, conceptual models are normally used as they are less demanding from a computational point of view. These conceptual models, frequently denoted as hydrological models, respect conservation of mass as well but use conceptual relations instead of momentum equations resulting in rapid simulations (Achleitner, Möderl, and Rauch 2007).

Consequently, two different models are often provided for the same sewer system, a hydrodynamic model for the hydraulic verification and a conceptual model for the assessment of CSOs. However, using only one model for both verifications has many advantages, e.g. it avoids double model-building as well as double model-maintenance. Only hydrodynamic models are applicable when only one model is used for both verifications since conceptual models are not suitable for the calculation of water levels for hydraulic verification.

However, the application of hydrodynamic models for the continuous simulation of a few years up to several decades in order to determine the overflow volume of CSOs can still lead to unacceptably long computation times. Several approaches to reduce the computation time of long-term hydrodynamic simulations have been developed like skipping steady state flow periods or using larger computational time steps during dry weather conditions, e.g. implemented in the Stormwater Management Model by US-EPA (Rossman 2015). The parallelization of the modeling engine or the execution of parallel simulation runs are other approaches (Mair et al. 2014). The computation time can also be reduced when a series of storm events, that excludes non-relevant simulation periods, is used instead of the precipitation continuum. This approach also enables parallel simulations on multiple cores and/or machines.

The separation of storm events is essential for many questions in the field of hydrology. Substantial literature reviews on this topic can be found in (Molina-Sanchis et al. 2016) and (Dunkerley 2008). The approaches used can vary greatly depending on the subject of study and on the time resolution of the data. According to Bonta and Rao (1988), two approaches can be used to identify independent storm events. The first approach considers both precipitation data and watershed conditions whereas in the second approach, only precipitation data are used. The most used criterion to separate storm events

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by a defined dry period is a minimum inter-event time (MIT). The literature shows a large variability of MITs used in previous studies ranging from 3 min to 24 h (Dunkerley 2008). The MIT affects the number of detected storm events as well as their characteristics, e.g. the precipitation sum, duration and mean intensity. Additional criteria for storm event identification are: minimum rain depth and minimum storm event duration required for an event to be recorded, minimum rain rate for a period within the event, minimum rain rate for the start of an event to be recognized and minimum rain rate marking the end of an event (Dunkerley 2008).

Existing methods to select storm events for a series simulation in urban drainage modeling were motivated by the hydraulic verification of sewer systems. They focus on detecting mainly short and heavy storm events with distinct intensity peaks which result in surcharged conditions (e.g. Verworn 1999). This method is not suitable for the assessment of CSOs as it does not consider filling and emptying phases of storage volumes in the system influencing the separation of storm events for the assessment of CSOs. Furthermore, long-lasting storm events with lower intensity are not considered.

This paper presents a method to select a series of storm events for the assessment of CSOs. This series comprises relevant storm events which contribute to overflow events. The separation of storm events is linked to the event history and system state at the start of a storm event, e.g. soil moisture, filling degree of storage tanks or depressions, etc. The method's parameters are optimized so that the series replicates the overflow volume of the continuous simulation while minimizing the overall computation time.

Methods

First, a method for selecting a series of storm events was developed. The method's parameters were subjected to a global sensitivity analysis to evaluate their effects on the simulated overflow volume.

After illustrating this storm event detection method using different parameter sets, the method's parameters were optimized using two objectives: (i) replicate the overflow volume of the continuous simulation and (ii) minimize the overall computation time of the series simulation. The aim was to identify general thresholds for separating storm events and for neglecting non-relevant storm periods. The reduction of computation time is based on excluding dry periods as well as small storm events which do not generate overflows and do not influence the simulation results regarding CSO volume and frequency of subsequent storm events. The separation of storm events enables parallel simulation of single storm events, further reducing the overall computation time.

For this work the Stormwater Management Model by US-EPA served as the modeling platform and all results were simulated in parallel.

Storm event detection (SED) method

The presented method utilizes four input parameters to select adequate series of storm events: (i) 'threshold-time' – T_t, (ii) 'threshold-value' – T_v, (iii) 'event gap' – G_e, and (iv) 'time extension' – t_e.

The method works as follows:

(i) The precipitation sum (PS) is determined for a certain time segment (T_t) and every time step as a rolling sum:

$$PS(t) = \int_{t}^{t-T_t} p(\tau)d\tau$$

(ii) The obtained $PS(t)$ is compared with T_v. Only if the obtained precipitation sum over T_t is larger than the selected T_v, the respective time period is considered for the final series of storm events:

if $PS(t) > T_V$:

consider period (t - T_t) for series of storm events

else:

do not consider period (t - T_t) for series of storm events

(iii) The time intervals (TI) between storm periods that are considered for the series of storm events are calculated and compared to G_e, which defines the minimum inter-event time that separates two storm periods. Only if the particular time interval is larger than G_e, two storm periods are separated to single storm events. Otherwise, the storm periods are handled as one storm event:

if TI > G_e:

split storm periods

else:

do not split storm periods

Thus, G_e deals with constraints for separating storm periods (initial system state) and ensures that two consecutive storm events are not influencing each other.

(iv) Finally, the determined events are extended by t_e as an overflow event does not necessarily stop immediately after the storm event. This last parameter is only relevant for simulations and does not influence the detection of storm events. t_e is limited by G_e as it cannot extend into the next storm event ($t_e \leq G_e$).

Figure 1 illustrates a schematic procedure of the SED method.

Global sensitivity analysis

A global sensitivity analysis (GSA) was conducted using the Morris Screening (Campolongo, Cariboni, and Saltelli 2007) for a first assessment of parameter influence on the simulated overflow volume.

The used GSA method works at low computational cost and provides the average (μ*) and standard deviation (σ) of local sensitivities obtained at different locations in the parameter space. A large value of μ* shows that perturbations of the investigated parameter significantly affect the model output averaged over the other parameters. Therefore, the output is generally sensitive to that parameter. A large value of σ implies that the effect of the investigated parameter is highly

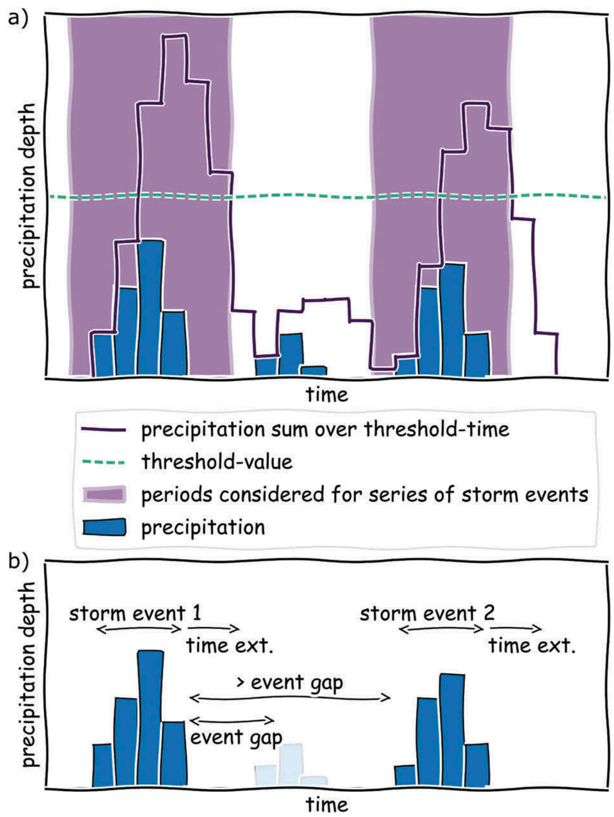

Figure 1. Scheme of the SED method; (a) The purple-colored continuous line illustrates PS(t) (T_t = 4 time intervals). The purple-shaded areas indicate the periods where PS(t) > T_v (turquoise-dashed line). The small storm period in the middle is not considered for the series as PS(t) < T_v . (b) The two remaining storm periods are separated as TI > G_e. Finally, storm events are extended by t_e.

affected by the choice of the point in the input space. This indicates non-linearity and/or interactions with other parameters.

The parameter space was restricted to positive values ($T_t > 0$, $T_v \geq 0$, $G_e \geq 0$, $t_e \geq 0$) under the condition $t_e \leq G_e$. The same parameter boundaries were also used for the optimization.

Illustration of the SED method

The effects of using different parameter sets for detecting storm events were investigated using the following six cases: (a) G_e = 360 min, T_v = 0 mm; (b) G_e = 1320 min, T_v = 0 mm; (c) G_e = 360 min, T_t = 60 min, T_v = 1 mm; (d) G_e = 360 min, T_t = 60 min, T_v = 10 mm, (e) G_e = 360 min, T_t = 10 min, T_v = 3 mm; (f) G_e = 360 min, T_t = 720 min, T_v = 3 mm. t_e was set to 0 in each case (a)-(f) since it does not affect the SED itself. The parameters were selected iteratively to show the effects of the particular parameters or parameter combinations. The used precipitation continuum was taken from precipitation time series 1 in Table 1 and had a length of six days.

Optimization

The parameters of the SED method were optimized using the following two objectives: (i) minimize the storm event time sum and (ii) maximize the total overflow volume. The event time sum is the summarized length/duration of storm events and, thus, the sum of simulation periods. It served as a surrogate measure of computation time as a smaller event time sum implies a smaller computation time. As the domain of application of the SED method is the assessment of CSOs, it has to provide results matching the continuous simulation. Therefore, it is necessary to maximize the overflow volume as an objective of optimization.

Figure 2 shows the general schematic procedure of the optimization. The single storm events were used as input for hydrodynamic simulations and the particular results for the overflow volume were summarized. Thus, for each parameter set of the SED method an event time sum and a total overflow volume were obtained. The multi-objective genetic algorithm (NSGAII – Deb et al. 2002) optimized the parameters to minimize the event time sum while maximizing the total overflow volume.

The optimization was applied to five virtual case studies (VCS) with varying system properties (VCS 1–5 in Table 1). The VCS were generated using the 'Case Study Generator' described by Möderl, Butler, and Rauch (2009) which uses the length of the urban drainage system, the slope of the catchment surface, the population and design rainfall intensity, etc. as input. The VCS used in this paper were taken from a set of 250 VCS calibrated on real-world case studies (RWCS) with alpine character.

Additionally, two different precipitation time series provided by OEWAV (2007) were used for the optimizations (no. 1 and 2 in Table 1). Hence, in total 10 optimizations were conducted (5 models x 2 precipitation time series). The pareto-optimal results meeting a maximal deviation of 3% from

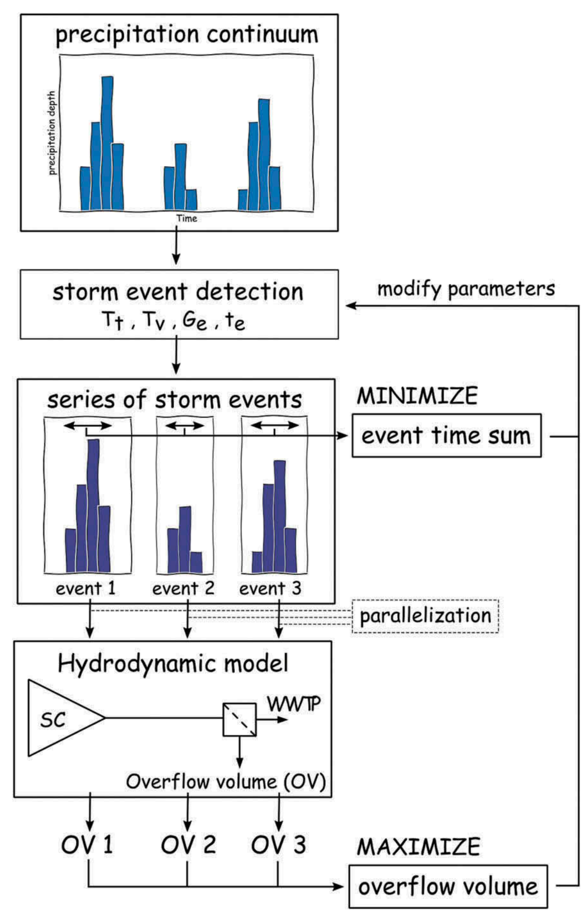

Figure 2. Schematic procedure of the optimization.

Table 1. Properties of case studies and precipitation time series.

No.	Number of CSO structures	Total area in ha	Impervious area in ha	Storage volume in m³	Avg. slope in %	Length of main sewers in km
Virtual case study properties						
1	11	1707	899	28,600	0.58	28.5
2	4	1527	755	32,500	0.75	24.9
3	6	1902	1000	25,800	1.27	29.4
4	9	772	393	14,200	0.98	21.5
5	9	5045	2656	111,500	1.15	59.1
6	9	4933	2044	53,300	0.99	56.3
7	8	1512	777	34,600	0.53	28.9
8	13	2384	1223	41,900	1.28	35.6
9	7	1418	745	20,000	1.41	36.2
10	8	1221	650	26,900	0.88	30.6
11	7	2088	1053	49,400	1.07	26.8
12	6	3207	1572	30,500	1.26	37.9
13	8	1471	737	24,200	1.48	22.6
Real-world case study properties						
14	5	1143	669	11,100	0.99	
15	1	457	95	0	0.04	
Precipitation time series						
No.	Location	Length in years	Ø annual precipitation sum in mm			
1	Graz I	5	826			
2	Eisenstadt I	5	732			
3	Baden	10	638			
4	Bregenz	10	1446			
5	Eisenstadt II	10	644			
6	Gmunden	10	1224			
7	Graz II	10	783			
8	Innsbruck	10	889			
9	Lienz	10	852			
10	Linz	10	875			
11	Luedinghausen	10	953			

the overflow volume of the continuous simulation were analyzed to identify a general parameter set that produced reasonable results for all 10 applications.

Validation

The validity of the ‘general’ parameter set was verified by applying it to eight different VCS (no. 6–13 in Table 1) and eight different precipitation continua (no. 3–10 in Table 1). Additionally, two real-world case studies with precipitation time series no. 11 and 7 (Table 1), respectively, were used for validation. A hydrodynamic simulation using the entire precipitation continuum served as ‘reference case’ to assess the performance of the selected series of storm events.

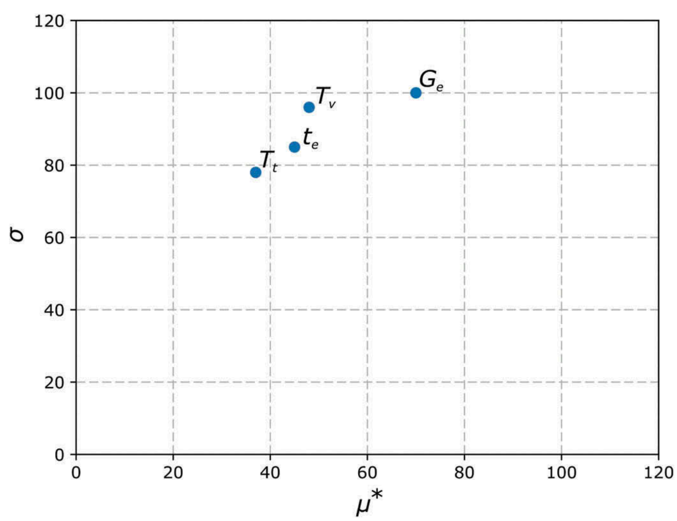

Figure 3. Result of the Morris Screening for total overflow volume.

Results

Global sensitivity analysis

The GSA used the total overflow volume as investigated model output variable. All parameters are sensitive (based on μ*) and the result suggests a non-linearity and/or interactions with other parameters (based on σ) as well (Figure 3). Therefore, all four parameters were taken into account for the subsequent investigations.

Illustration of the SED method

Figure 4 shows the results of the SED method using the different parameter sets of cases (a)-(f). Different parameter combinations result in a different number of detected storm events as well as different durations of detected storm events. Increasing G_e between case (a) and (b) results in detecting only two instead of four storm events. Applying thresholds in cases (c) and (d) shortens the detected storm events or reduces the number of detected storm events. Using a higher value for T_t in case (f) compared to case (e) results in longer storm events and the detection of one storm event less.

Optimization

The optimization result for VCS 4 is presented in Figure 5. Each parameter set of the SED method results in a certain event time

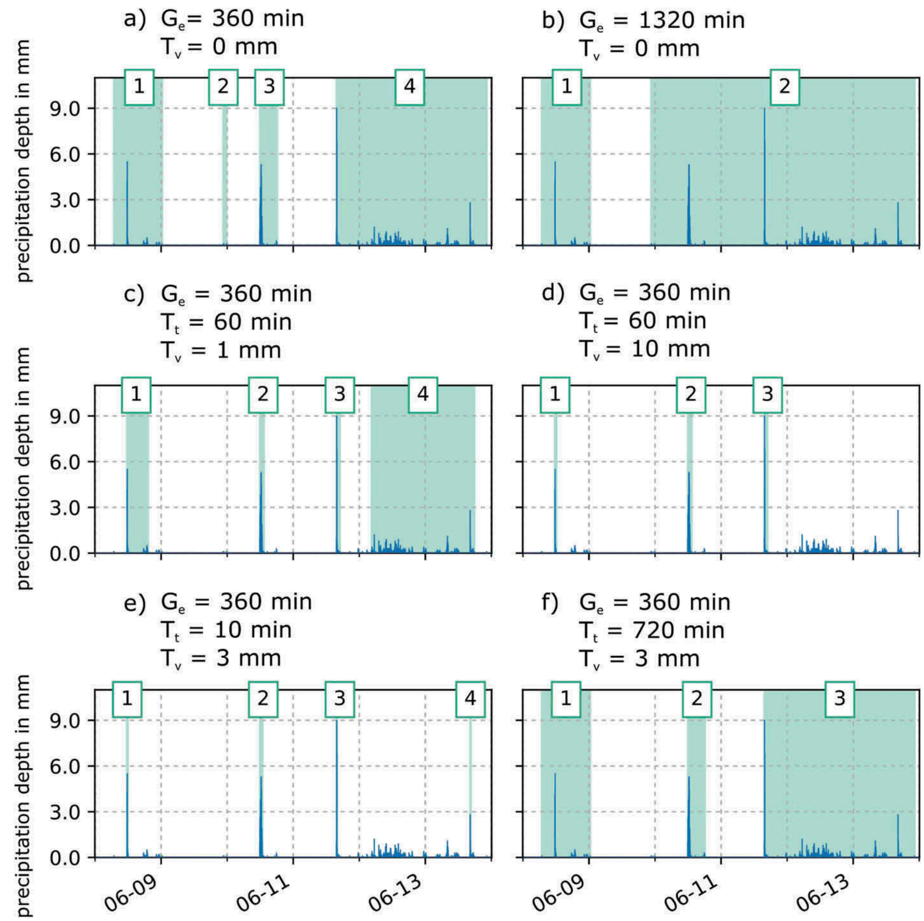

Figure 4. Illustration of the SED method using different parameter sets; the color-shaded and numbered areas indicate the detected storm events.

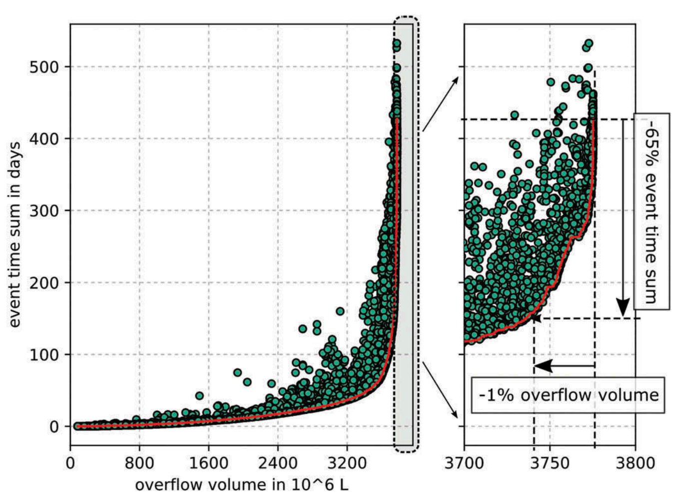

Figure 5. Result of the optimization using case study 4 and precipitation time series 1; Every dot represents the result of a specific parameter set of the SED method. The red curve indicates the Pareto front.

sum and a certain overflow volume after simulating the series of storm events. This is illustrated by the dots of the scatter-plot. The result of the optimization clearly shows a Pareto front.

Figure 5 also shows a detailed view of results with a large overflow volume. It is evident that the simulation of only 427 days, instead of 1825 days in the reference case, is necessary to get the maximal overflow volume that equals the overflow volume of the reference case of 3775×10^6 L. Hence, the simulation period can be reduced by 77% to get the appropriate overflow volume. In addition, accepting only a minimum degree of imprecision in overflow volume leads to further reductions of the event time sum. In the investigated case, reducing the overflow volume by 1% resulted in an additional event time sum reduction of a further 65%, compared to the storm event series generating the maximal overflow volume. In total, the precipitation continuum is reduced by 92% in this case.

The analysis of all pareto-optimal parameter sets, accepting a small deviation from the overflow volume using the precipitation continuum, revealed a parameter set that works generally. Hence, this parameter set is not the optimal one for every particular case, but results in considerable reductions of computation time and an overflow volume which deviates only 2.05% in the mean with a standard deviation of 1.3% from the result of the reference case. The values of the general parameter set are as follows:

T_t = 700 min
T_v = 6 mm
G_e = 1400 min
t_e = 100 min

Each optimization shows a case study-specific, particular optimal parameter set with respect to a maximal overflow volume, thus, resulting in the same overflow volume as

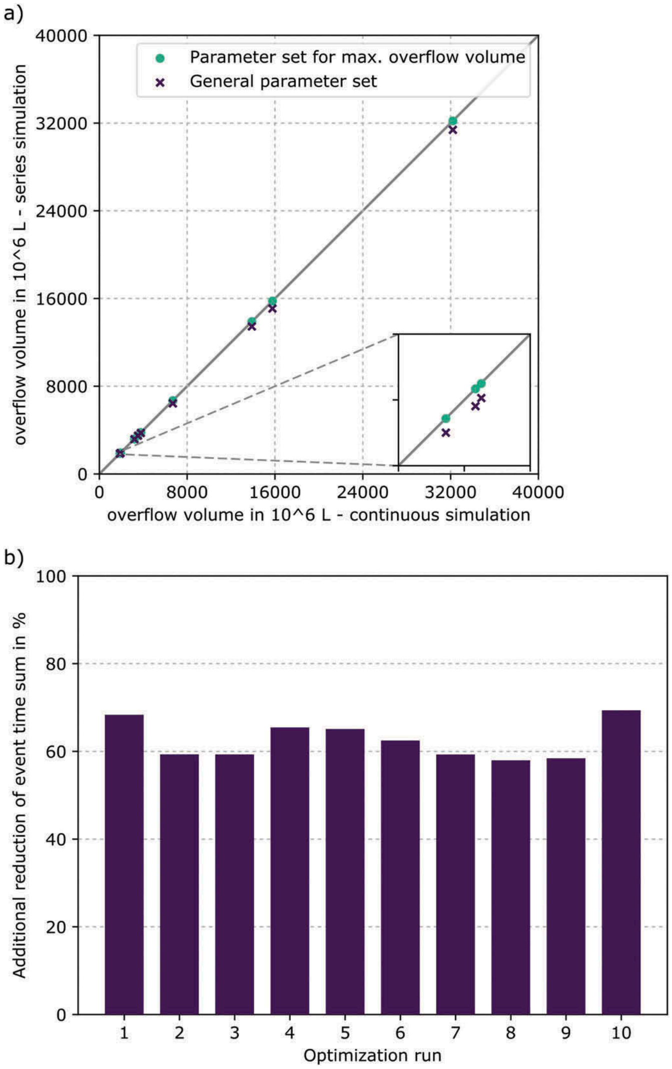

Figure 6. Results of optimization tasks. (a) Overflow volume with continuous simulation versus overflow volume with series simulation using particular parameter set for maximal overflow volume (turquoise points) or general parameter set (purple crosses); (b) Reduction of event time sum using the general parameter set instead of the parameter set resulting in a maximal overflow volume for the particular optimization.

using the precipitation continuum. Figure 6(a) shows a comparison between applying these particular optimal parameter sets with respect to a maximal overflow volume and applying the general parameter set for the 10 possible combinations of case studies and precipitation time series. Remarkably, the results using the general parameter set are very close to the results using the precipitation continuum.

The event time sum is reduced when using the general parameter set instead of the particular optimal parameter set with respect to a maximal overflow volume (Figure 6(b)) due to accepting a small inaccuracy of the resulting overflow volume. The reduction ranges between 58% and 70%.

Validation

The general parameter set was applied to eight different VCS and eight continuous precipitation time series of 10 years. Figure 7(a) shows a comparison of the overflow volume estimated using the continuous time series with the overflow volume estimated using the series of storm events. An exact accordance of continuous simulation and series simulation would be optimal. This is represented by the 45°-line in Figure 7(a). Obviously, the results (blue dots) are very close to this optimum. A linear regression shows an R-Value of 0.99. The deviation of the overflow volumes from the optimal case shows a mean value of 1.95% with a standard deviation of 1.36%.

Additionally, two real-world case studies with the appropriate precipitation time series of 10 years were used for validation. The overflow volume of the series simulation deviates from the continuous simulation by 4.1% and 0.1%, respectively.

Figure 7 also shows the impact of applying the general parameter set to the precipitation time series 3–10 on the event time sum. It varies between 177 and 503 days (Figure 7(b)), whereas the continuum has a length of 3652 days (reduction between 86.2–95.2%).

The rain periods in the precipitation continuum as well as in the series of storm events were summarized and illustrated in Figure 7(c). The application of the general parameter set results in a reduction of rain periods between 17.6% and 38.0%.

Discussion

Figure 4 shows the effects of using different parameter sets for storm event detection. The higher the selected G_e is, the fewer storm events are detected as it is less probable to detect longer time intervals between the considered storm periods (cases (a) and (b)).

The application of a higher T_v can have several consequences, shown in cases (a), (c) and (d): elimination of storm events, splitting of storm events, decrease of storm event length.

The longer the selected T_t, the longer the periods considered for the storm event series are as it is more probable to exceed a fixed T_v (cases (e) and (f)). On the one hand, this results in longer storm events detected, on the other hand, this can lead to less storm events detected as the time between the considered periods does not exceed the chosen G_e anymore.

When using the series of storm events instead of the precipitation continuum for the assessment of CSOs, the overflow volume has to be estimated as accurately as possible. Therefore, only results in the grey-colored area of Figure 4 can be taken into account. The analysis of these results showed that accepting only a minimum degree of imprecision in the overflow volume (e.g. 1%) leads to further reductions of the event time sum (compare also Figure 6(b)).

Considering the manifold uncertainties in the context of urban drainage modeling regarding model input, calibration or model structure (compare Deletic et al. 2012), a deviation of 2–3% or accuracy of 97–98% for the overflow volume is acceptable. This assumption resulted in the identification of a general parameter set. The general G_e of approx. 24 h is mostly motivated by the emptying time of storage tanks and ensures that two consecutive storm events do not influence each other regarding the initial system state. The value of 24 h lies on the upper edge of the scope between

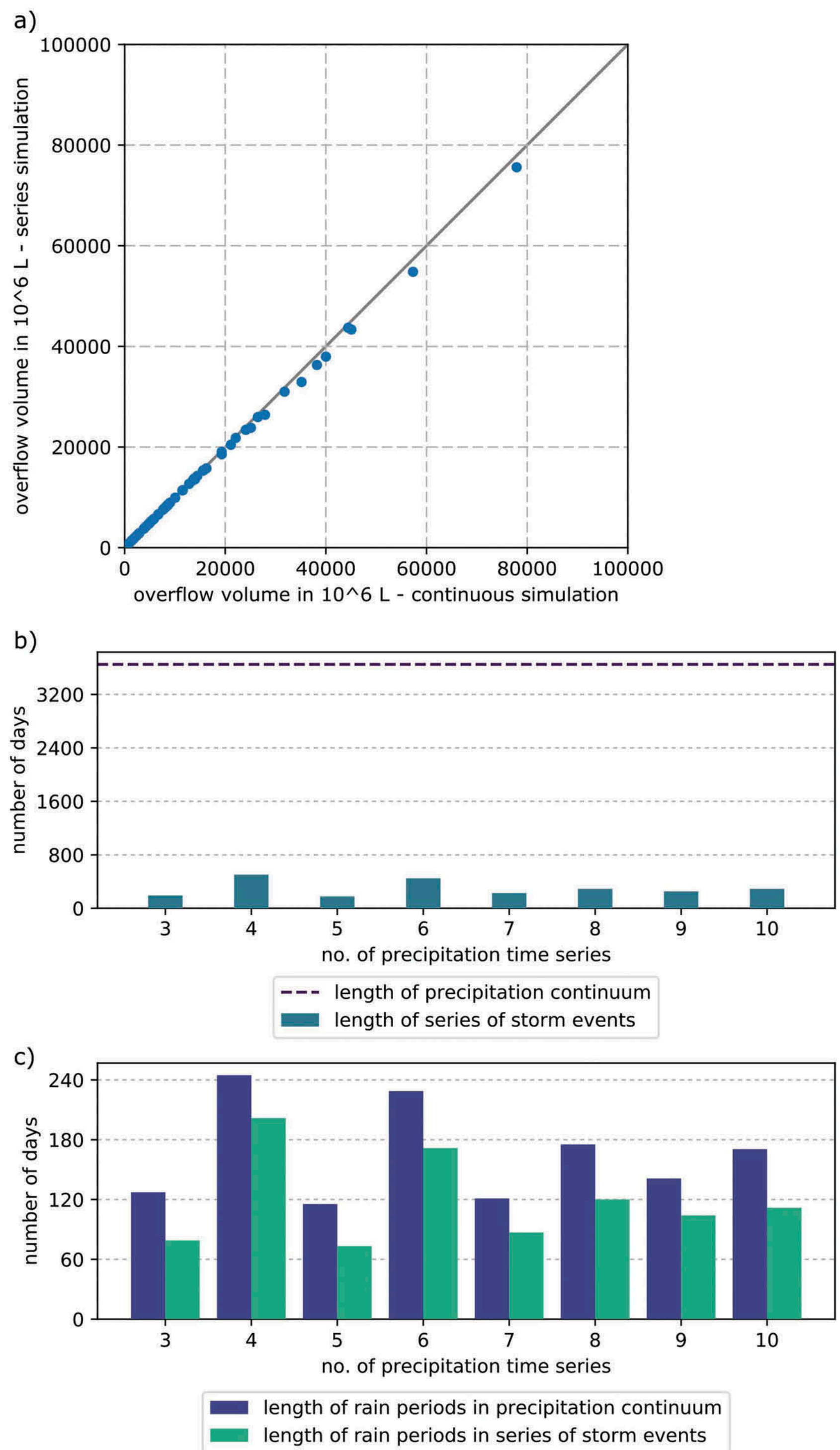

Figure 7. (a) Validation of the general parameter set: Comparison of the overflow volume obtained by using a continuous simulation with using a series simulation (using the general parameter set); (b) Comparison between the length of the precipitation continuum and the length of the series of storm events; (c) Comparison between the length of the rain periods in the precipitation continuum and in the series of storm events.

3 min and 24 h used as MIT in previous studies (Dunkerley 2008).

The series simulations with a series of storm events selected by using this general parameter set accurately replicate the result of the continuous simulations (Figures 6(a) and 7(a)).

Beside the general applicability, the advantage of the general parameter set is a further reduction of the event time sum compared to using the case-specific optimal parameter set with respect to a maximal overflow volume (Figure 6(b)).

The SED method using the general parameter set considerably reduces the simulation periods compared to the precipitation continuum (Figure 7(b)). The main fraction of the reduction results from excluding dry periods. However, also a non-negligible fraction of the rain periods is excluded by using the SED method

(Figure 7(c)). This reduction is especially valuable since rain periods are very computation-time-intensive in hydrodynamic simulations.

In addition to reducing simulation periods (Figure 7(b)), the main benefit of using a series of storm events lies in enabling parallel simulations of particular storm events on a multi-core CPU or on several computers. Thus, an additional reduction of the overall computation time is achieved.

Conclusions

Conducting the hydraulic verification of combined sewer systems and the assessment of CSOs with only one hydrodynamic model has many advantages, e.g. no double model-building nor double model- and data-maintenance.

To achieve reasonable computation times, we showed that using only a series of relevant storm events instead of the precipitation continuum is sufficient for calculating the overflow volume. A simple method was developed to select this series. The method's parameters were optimized to replicate the overflow volume of the continuous simulation and to minimize the computation time. A generally applicable parameter set was identified which reproduced the overflow volume of the continuous simulation with a mean error of only 1.95% (standard deviation of 1.36%) for the VCS and an error of 4.1% and 0.1% for the real-world case studies used for validation.

The series of storm events is considerably shorter than the precipitation continuum (reduction between 86.2–95.2% for investigated cases) due to the exclusion of dry periods as well as storm periods which do not generate overflow events (reduction of rain periods between 17.6% and 38.0% for investigated cases). This leads to a reduction of computation time. Moreover, parallel simulation of single storm events on multi-core CPUs or on several computers is possible. This additionally reduces the overall computation time.

The proposed method can be used for different applications of CSO assessments, e.g. verification purposes, uncertainty analyses and adaptation scenarios. Especially in cases where a large number of simulations are conducted, the method is valuable because of the speed-up compared to using a precipitation continuum.

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Disclosure statement

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