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Efficient integration of IoT-based micro storages to improve urban drainage performance through advanced control strategies

Martin Oberascher, Wolfgang Rauch and Robert Sitzenfrei

ABSTRACT

The smart rain barrel (SRB) consists of a conventional RB with storage volumes between 200 and 500 L, which is extended by a remotely (and centrally) controllable discharge valve. The SRB is capable of releasing stormwater prior to precipitation events by using high-resolution weather forecasts to increase detention capacity. However, as shown in a previous work, a large-scale implementation combined with a simultaneous opening of discharge valves clearly reduced the effectiveness. The aim of this work was to systematically investigate different control strategies for wet weather by evaluating their impact on sewer performance. For the case study, an alpine municipality was hypothetically retrofitted with SRBs (total additional storage volume of 181 m^3). The results showed that combined sewer overflow (CSO) volume and subsequently pollution mass can be reduced by between 7 and 67% depending on rain characteristics (e.g., rain pattern, amount of precipitation) and an applied control strategy. Effectiveness of the SRBs increases with lower CSO volume, whereas more advanced control strategies based on sewer conditions can clearly improve the system's performance compared to simpler control strategies. For higher CSO volume, the SRBs can postpone the start of an CSO event, which is important for a first-flush phenomenon.

Key words | IoT-based solution, real-time control, Smartin toolbox, smart rainwater harvesting, weather forecasts, wet weather

Martin Oberascher
Wolfgang Rauch
Robert Sitzenfrei (corresponding author)
Unit of Environmental Engineering, Department of Infrastructure Engineering, Faculty of Engineering Sciences,
University of Innsbruck,
Technikerstrasse 13,
6020 Innsbruck,
Austria
E-mail: *robert.sitzenfrei@uibk.ac.at*

HIGHLIGHTS

- An alpine municipality is hypothetically retrofitted with 384 smart rain barrels (SRBs) as an IoT-based solution for micro storages utilised for smart rainwater harvesting.
- Control strategies based on sewer conditions show a clear improvement in the system's performance compared with without considering sewer states.
- Efficiency is particularly high if overflow volume is in relation to storage volume of the SRBs implemented.

INTRODUCTION

Rainwater harvesting (RWH) systems aim to substitute drinking water in non-potable water applications (e.g., irrigation, toilet flushing) by retaining rainwater runoff in decentralised storage tanks (Campisano *et al.* 2017). Due to detention of precipitation, RWH systems reduce runoff into drainage systems, and a large-scale implementation can therefore improve system performance (e.g., urban flood management) (Jamali *et al.* 2020). However, the efficiency of stormwater detention is strongly dependent on withdrawal quantities. For example, higher withdrawal volumes during warm periods empty the storage tanks

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faster, and, consequently, more storage volume for rainwater detention is available (Quinn *et al.* 2020).

The development of the Internet of Things (IoT) concept as part of Smart Cities opens up new possibilities in management of urban water infrastructure. For example, innovative communication technologies (e.g., LoRa, NB-IoT, and Sigfox) in combination with low-cost sensors, enable a system-wide inclusion of communicating items (Li *et al.* 2014). An exemplary application is a decentralised rainwater storage unit, which is capable to control outflow in real time. In this context, Xu *et al.* (2020) investigated the benefits of weather forecasts for real-time controlled storage tanks at catchment scale, showing that discharges – prior to precipitation events – reduced uncontrolled overflows. Additionally, Di Matteo *et al.* (2019) and Liang *et al.* (2019) demonstrated in a simulation-based approach, that a coordinated control between two storage units can reduce peak runoff rate of roof areas even for rare rain events. In contrast, Roman *et al.* (2017) also considered irrigation requirements in the control strategy, thus improving both, detention capacity and drinking water savings.

Previous studies have mainly focused on smart storage tanks greater than 1 m^3. In this context, Oberascher *et al.* (2021) introduced the smart rain barrel (SRB) concept as an IoT-based solution for micro storage with storage volumes between 200 and 500 L. The SRB is utilised for advanced rainwater harvesting and consists of a conventional RB available in normal hardware stores, which is extended by a remotely (and centrally) controllable discharge valve. To tackle the two contracting objectives, i.e. (1) discharge of rainwater to provide additional storage volume, and (2) detention of rainwater for irrigation purposes, high-resolution weather forecasts are added into the control strategy in that work. Measurement data (e.g., filling level) and control commands (e.g., open discharge valve) are exchanged via LoRaWAN, which allows an integration into a smart city development. The effectiveness of the SRB concept was demonstrated by a two-stage approach: (1) development and operation of a protype and (2) model-based investigation of retrofitting a real urban water infrastructure system with a large number of SRBs. The results showed that the SRBs can clearly improve overall system performance of urban drainage and water supply network by reducing combined sewer overflow volume and providing a sufficient amount of rainwater to substitute drinking water for irrigation purposes. However, a simplified control strategy for wet weather was utilised, and all discharge valves were opened simultaneously if precipitation was forecasted. Consequently, if sewer conditions were unfavourable, e.g., a partly filled combined sewer overflow (CSO) due to a previous rain event, the uncontrolled opening resulted in artificial CSO events and reduced the effectiveness of the SRB concept.

The aim of this work is to improve the control strategy for the SRB concept during wet weather. Therefore, different control strategies (e.g., grouped emptying, opening in combination with the (hydraulic) state of the sewer and model predictive control) are applied, and impacts are evaluated in terms of CSO events and flood volume. For a case study, the existing urban water infrastructure of an alpine municipality was hypothetically retrofitted with SRBs, providing an additional storage volume of 181 m^3.

METHODS

Integrated urban water management with micro storages – 'Smartin' tool box

The open-source software 'Smartin' (Oberascher *et al.* 2021), available under https://github.com/iut-ibk/Smartin-Toolbox/tree/master/smartin, was used for simulations. 'Smartin' is capable of modelling real-time controlled micro storages developed as IoT-based solutions in a coupled model of urban drainage and water supply network in very high spatial and temporal detail. The software is based on several Python packages, including PySWMM (McDonnell *et al.* 2020) as a Python wrapper for the hydrodynamic stormwater management model (SWMM5), and Python EPANET Toolkit provided by Open Water Analytics (https://github.com/OpenWaterAnalytics/epanetpython/tree/dev/epanet_python/epanet_python) for EPANET2.2 (Rossman *et al.* 2020).

In 'Smartin' the SRBs are implemented as low impact development (LID) type RB into SWMM5, and outflow is individually controlled by changing the drain coefficient. Additionally, high-resolution weather forecasts are applied to estimate future inflows into each of the implemented SRB, and, if the estimated inflow exceeds available storage volume, the discharge valve of the SRB is opened. In cases in which estimated inflow is lower than the total storage volume (equal to RB volume), the discharge valve is closed if the available detention volume matches exactly the estimated inflow to ensure a fully filled SRB at end of the forecast period. In contrast, if the estimated inflow exceeds the total storage volume, the discharge valves are closed before the period with expected peak intensity. During dry weather periods, the stored rainwater is used for irrigation and daily irrigation demand is calculated based on crop evapotranspiration. In this work, a forecast period (referred as accumulation time in the following) of the weather forecast of 4 h is assumed, whereas the update time step is 2 h. Originally, a simplified control strategy was implemented in 'Smartin', in which discharge valves of all implemented micro storages were opened simultaneously (hence denoted '**SRB all**' in the following). However, simultaneous opening could worsen system performance if sewer conditions were unfavourable. Consequently, 'Smartin' was extended here by three additional control rules to improve overall system performance during storm events. The control strategies are implemented as a heuristic controller (if-then based) to manage the additional storage volume provided by the SRB implemented and can be described as follows:

- **SRB grouped**: In this control strategy, the SRBs implemented are randomly subdivided into four groups, and the control groups are staggered emptied in 30 min steps.
- **SRB CSO depth**: The discharge valves of the implemented SRBs are opened simultaneously, but the opening is dependent on actual system states. Therefore, filling depth in the CSO structure (total depth of 2.3 m) is considered in the control strategy, and a threshold is defined. In this work, the threshold is set to be 1.0 m. Consequently, discharge valves are only opened if the actual filling depth in the CSO structure at the update time step is below this threshold ($<$1.0 m), whereas in the opposite case (filling depth $\geq$1.0 m), all discharge valves remain closed.
- **SRB MPC**: In the third control strategy, model predictive control (MPC) is applied to optimise future control (the handle variable is number of discharge valves opened in this work), and can be summarised as: (1) actual filling depth of SRBs and sewer is determined and based on future weather forecasts, a simplified SWMM5 model is created; (2) discharge valves of 100% of SRBs are opened, and CSO volume is evaluated; and (3) if there is no CSO event, settings are adopted into control strategy, whereas in the case of a CSO event, the number of SRBs is reduced by 20% randomly and step (2) is repeated.
- **Uncontrolled RBs**: Performance of conventional (equivalent to uncontrolled) RBs is used as a reference state in this work to investigate the impacts and effectiveness of different control strategies.

Performance evaluation

Flood volume and CSO performance are used as indicators to evaluate the effectiveness of control strategies applied for wet weather. For CSO performance, hydraulic stress and ammonia toxicity are commonly defined short-term impacts of CSO in technical regulations (Riechel *et al.* 2016). Therefore, overflow volume and ammonium (NH_4) concentration are chosen as performance indicators. Additionally, this approach is extended to include other harmful substances such as (heavy) metals, e.g., copper (Cu) and cadmium (Cd). Roof areas are a widespread source for copper, and as the SRBs concept aims to retain roof runoff, copper is considered as performance indicator too.

For the case study, no data about quality measurements are available. As stated in previous publications, event mean concentrations (EMCs) are associated with high uncertainties, but the approach is often used by practitioners and considered as usable in the lack of further data (Tuomela *et al.* 2019). Therefore, pollution wash-off is simulated by applying EMC during rain events, and the used pollution concentrations are summarised for different surface types and sewers in Table 1.

Case study

The different control strategies were tested by hypothetically retrofitting an existing urban drainage system of an alpine municipality located in Austria with SRBs. The municipality is drained by a combined sewer system, and network characteristics can be seen in Figure 1. Furthermore, the (in reality) overdesigned combined sewer overflow structure is re-dimensioned to meet minimum requirements of Austrian standards (new storage volume of 154 m^3). For simulations, the calibrated SWMM5 input file of Oberascher *et al.* (2021)

Table 1 | Mean pollution concentrations derived from publications for different surface types (Gobel *et al.* 2007; Riechel *et al.* 2020) and sewer flow (Gasperi *et al.* 2008)

Type	NH_4-N (mg/L)	Cu (μg/L)	Cd (μg/L)
Roof	3.39	153	0.8
Green area	0.8	11	0.7
Traffic (yard)	0.1	23	0.8
Traffic (yard industry)	0.1	80	1.2
Traffic (street)	0.1	86	1.6
Sewer	25	81	0.5

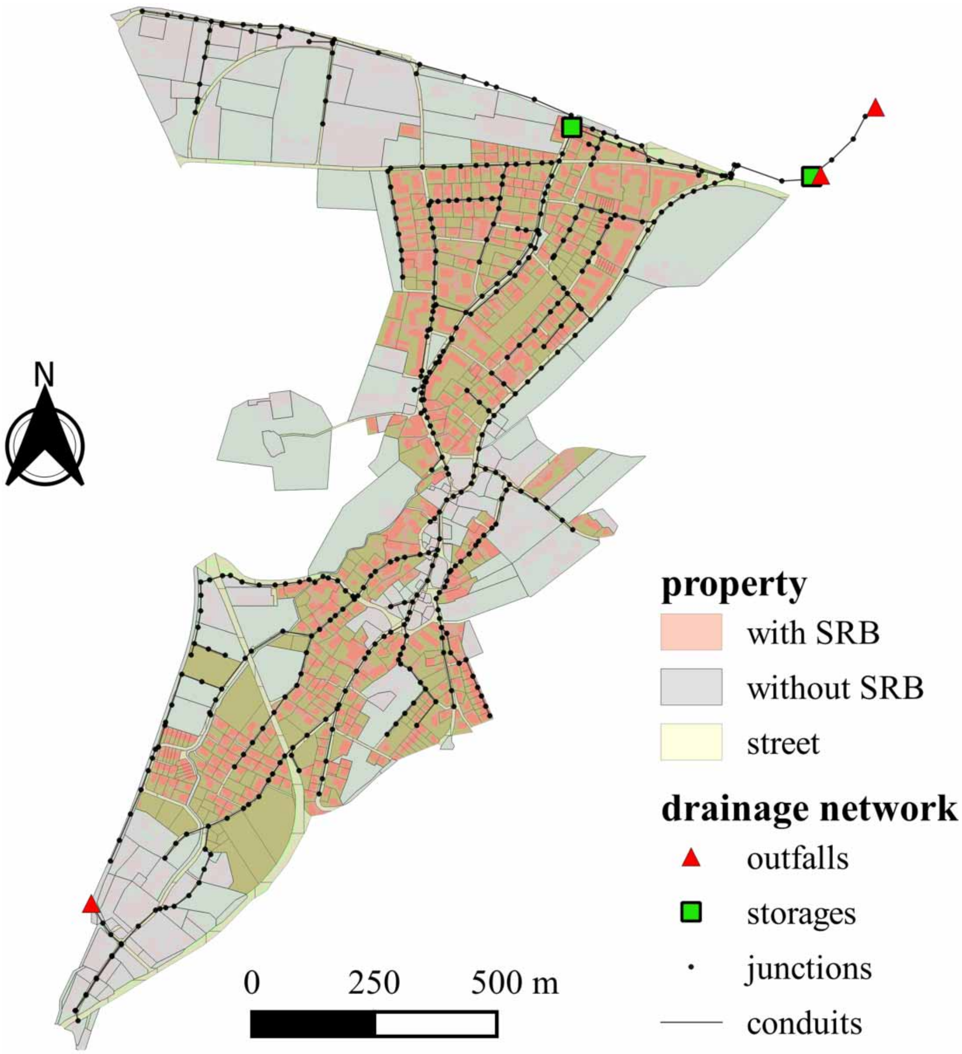

Figure 1 | Overview of the case study subdivided into properties with SRBs and without SRBs, and urban drainage network characteristics.

is used. The input file includes details on property level, and 630 properties with an area of 15.2 ha are connected to the urban drainage system. Properties in land classified as residential area, mixed-use area, and agricultural area are selected as installation places, as buildings in these areas have space for installation and green areas for irrigation. Therefore, 384 properties (roof area of 8.16 ha) are equipped with SRBs, whereas each property is further subdivided into green, traffic, and roof areas. For the SRBs, real RB sizes (200, 300, and 500 L) are chosen, which are available in normal hardware stores. The SRB size depends on the connected roof area, and a precipitation quantity of 6 mm is chosen as the reference value for choosing SRB size. In total, these SRBs provide an additional storage volume of 181 m^3. Additionally, properties with SRBs are highlighted in Figure 1. For more details on the case study, reference is made to Oberascher et al. (2021).

For the control strategy 'SRB MPC', a simplified SWMM5 model is created to predict future system states. The model consists of one big sub-catchment and the CSO structure, and the model is calibrated and validated with PCSWMM (CHI) based on data from a measurement campaign (rain data, and one flow measurement) between June and September 2017.

Climatology

Precipitation data available in 1 min time steps are extracted from a nearby weather station for 2018. In Austria, irrigation occurs mainly during the summer half-year (21 March to 23

September) (Neunteufel *et al.* 2014). Consequently, no rainwater is extracted from uncontrolled RBs outside this period and, therefore, no additional detention volume can be provided. In contrast, SRBs can be emptied automatically but, to compare results, the summer half-year 2018 was chosen as the simulation period. First, three characteristic rain events are extracted with total rain sum between 7.9 and 11.3 mm to test different control strategies, whereas maximum rain intensity is in the range of 0.1 and 1.3 mm/min (Table 2). The rain events cause a CSO volume of 210, 447, and 833 m^3, respectively, and the latter also had a flood volume of 3.9 m^3. Second, the total rain series of the summer half-year 2018 is applied for simulations to investigate the impact of different control strategies over a longer period. Precipitation data are available in 1 min steps and total precipitation amount is 424 mm for the summer half-year 2018, whereas daily precipitation varies between 0 and 32 mm/day (Figure 2). To model frequent extractions of rainwater for irrigation purposes, temperature data, available in a temporal resolution of 10 min, are utilised to calculate daily irrigation demand. Daily mean temperature ranges from −3 to 25 °C and temporal progression over the summer half-year is shown in Figure 2.

Table 2 | Rain characteristics of the investigated rain events and caused CSO and flood volume in the reference state without any SRBs

Rain	Day	Total rain sum (mm)	Max. rain intensity (mm/min)	CSO volume (m^3)	Flood volume (m^3)
Event 1	15 July 2018	7.9	0.8	210	0
Event 2	29 March 2018	12.9	0.1	447	0
Event 3	10 May 2018	11.3	1.3	833	3.9

Weather forecasts are one of the key elements of control, and are here integrated from the integrated nowcasting through a comprehensive analysis (INCA) system (Haiden *et al.* 2011). The INCA system is applied for mountain terrain and is based on 1 km grid cells, and supports numerical weather forecast models to represent the changing topography of the Alps. For the case study, weather forecasts are available for the next 24 h in 15 min steps for every 15 min.

RESULTS AND DISCUSSION

Illustration of CSO performance

Figure 3 illustrates the functionality of different control strategies for the SRBS applied to the real rain event 2 on 29 March 2018. As can be seen in Figure 3(a), the rain event is non-continuous and frequently interrupted with rain breaks. This effect is also reflected in filling of the CSO (Figure 3(b)), showing an increase during phases with precipitation and a decrease during rain breaks for the reference state without any RBs. However, a complete emptying of the CSO is not achieved during the investigated rain event. If the filling depth of the structure exceeds 2.3 m, an overflow occurs (Figure 3(d)), whereas two events can be identified during the investigated period. The total overflow volume is 447 m^3 for the reference state. Time series of pollution concentrations (NH_4-H, Cu, and Cd) are similar to the overflow volume as pollution wash-off is simulated with EMC, therefore reference is made to the results summarised in Table 3.

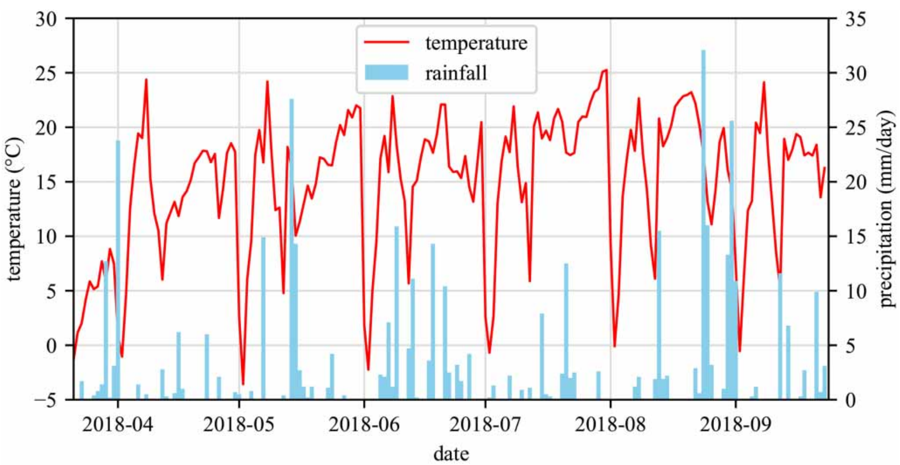

Figure 2 | Daily mean temperature and precipitation sum during the investigated summer half-year 2018.

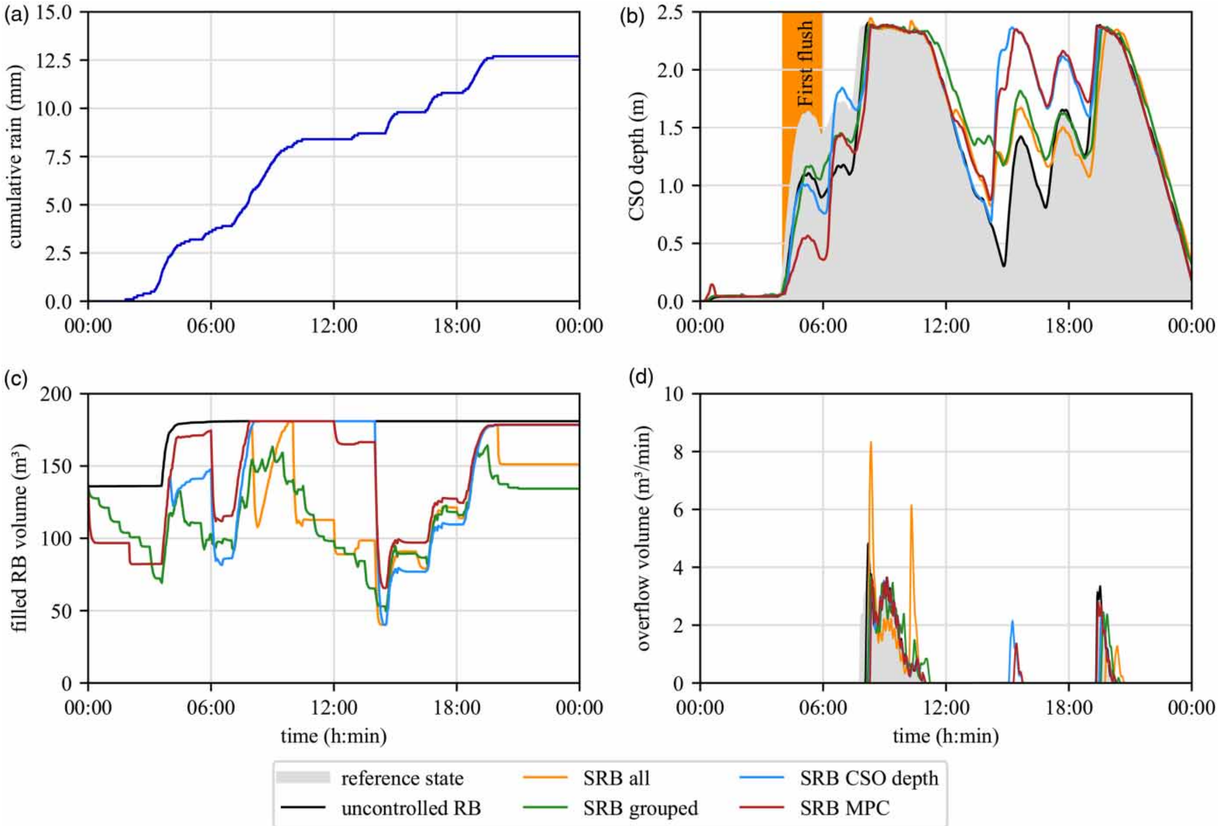

Figure 3 | Illustration of the functionality of different control strategies for the real rain event 2 on 29 March 2018: (a) cumulative rain sum, (b) CSO depth, (c) filled rain barrel volume, and (d) combined sewer overflow volume into receiving waters.

Table 3 | Results of performance indicators for a real rain event on 29 March 2018

Type	Overflow volume (m^3)	NH_4-N (kg)	Cu (g)	Cd (μg)
Reference	447.40	3.94	56.44	334
Uncontrolled	408.06	3.51	51.59	3,050
SRB all	377.05	3.30	47.04	281
SRB all (perfect)	315.80	3.04	35.35	214
SRB grouped	381.86	3.39	47.01	282
SRB grouped (perfect)	309.49	3.07	35.17	213
SRB CSO depth	362.47	3.29	41.81	253
SRB CSO depth (perfect)	294.17	2.87	35.40	216
SRB MPC	361.41	3.27	43.70	263
SRB MPC (perfect)	313.58	3.01	37.75	228

Figure 3(c) shows the filled RB volume over the duration of the rain event. Considering a longer event, the impact on the sewer increases with a higher initial volume, as less additional detention volume is available, and thus more stormwater is discharged before or during the rain event. Therefore, a very high initial volume of the RBs was assumed as the focus of this work was to improve wet weather control strategies including CSO performance for IoT-based micro storages. In this work, initial filling was randomly set between 50 and 100%, and filled RB volume is around 135 m^3 at the beginning of the investigated period (in contrast, total storage volume of the SRBs is 181 m^3). With first precipitation, the uncontrolled RBs are completely filled, and since no water is withdrawn for irrigation, the level remains constant for the rest of the period. However, despite the low empty storage volume (as the difference between total storage volume of 181 m^3 and filled RB volume) the uncontrolled RBs cause a reduced filling of the CSO at the beginning. Afterwards, filling depth and overflow volume correspond to the reference state. For the uncontrolled RBs, total overflow volume is 408 m^3 (39 m^3 less than the reference state).

In contrast, all SRBs are emptied at the beginning of the investigation period (as rain is forecasted) and filled RB volume decreases from 135 m^3 to approximately 80 m^3. Consequently, there is a small runoff peak noticeable

(Figure 3(b)), which is less obvious in cases of staggered emptying. Additionally, trajectories of the control strategies 'SRB all', 'SRB CSO depth' and 'SRB MPC' are equal at the beginning, and in the following, first differences occur when CSO event is expected in 'SRB MPC' or filling depth in the CSO structure is higher than 1.0 m. Afterwards, with start of precipitation, the SRBs begin to fill again and can thereby significantly reduce the first runoff peak in the sewer system. In this example, the first runoff peak induces no CSO overflow, but it highlights that the SRBs can postpone the start of CSO events which is important for first-flush phenomenon. However, due to different control aims, each SRB control strategy has a different pattern from that point on. For a better identification of the individual processes, reference is made to Figure 4, which shows a detailed section in the period from 06:00 to 12:00. Particularly noticeable are the overflow peaks of the control strategy 'SRB all', which are approximately twice as high as the reference state. In this control strategy, discharge valves of SRBs implemented are opened simultaneously, resulting in an artificial runoff wave in the sewer. Consequently, as conditions are unfavourable due to an already filled CSO structure and further precipitation at this time, peak overflow volume is increased rapidly. However, these simultaneous discharges have the advantage, that storage volume becomes more quickly available, and therefore, the second overflow event can be reduced significantly. Over the whole rainfall event, CSO overflow volume can be reduced by 70 m^3 compared to the reference state. Interestingly, the control strategy 'SRB grouped' has the least improvement compared to uncontrolled RBs (reduction of 65 m^3). In this control strategy the SRBs are divided into subgroups that are staggered emptied. Therefore, peak runoff rate in the sewer is decreased, which helps to avoid artificial CSO events. In contrast, decrease of filled RB volume is slower than with other control strategies. Consequently, a lower detention volume can be provided compared to the control strategy 'SRB all', which increases overflow volume.

Control strategies with the best improvements are 'SRB CSO depth' and 'SRB MPC', which reduce overflow volume by 85 and 86 m^3, respectively. Discharge valves of the SRBs are only opened if the filling level in the CSO is below a certain level or no CSO event is expected in the future, thereby reducing the risk of an artificial runoff wave. However, this example shows also that these two control strategies are strongly dependent on future weather development and

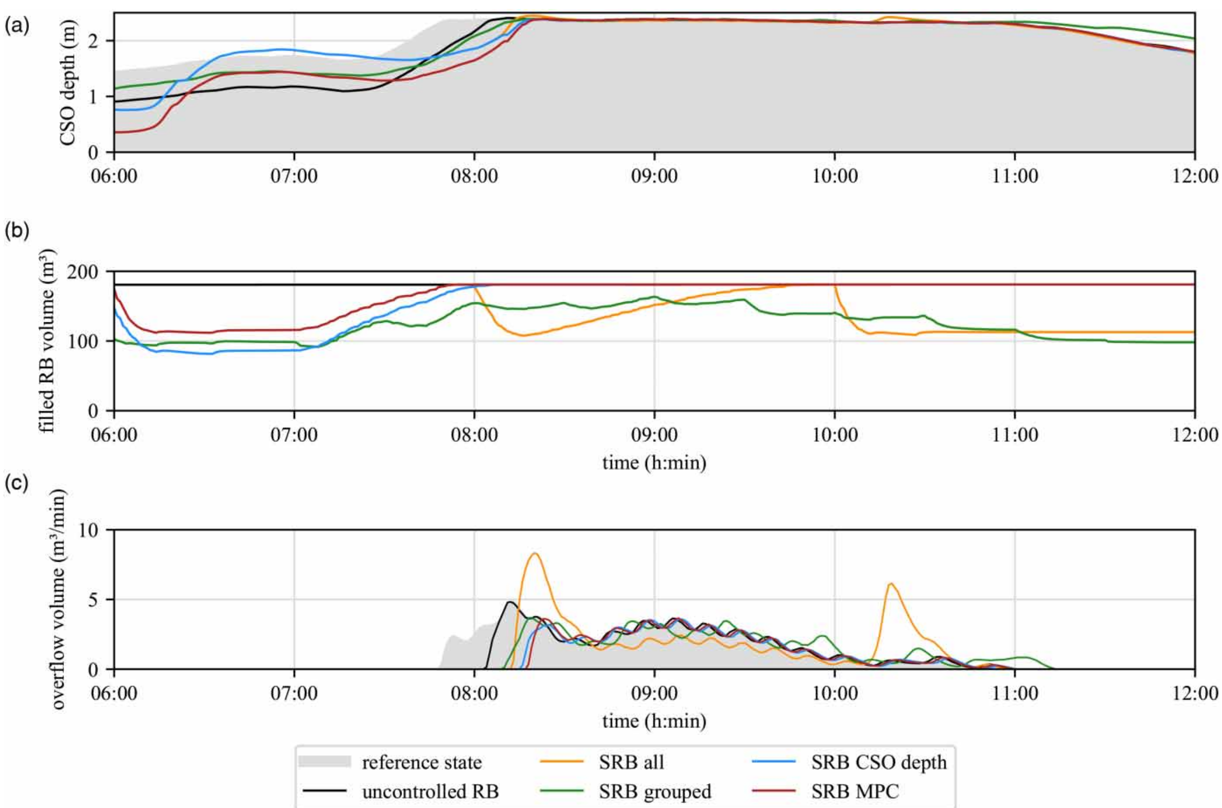

Figure 4 | Detailed section of the real rain event 2 on 29 March 2018: (a) CSO depth, (b) filled rain barrel volume, and (c) combined sewer overflow volume into receiving waters.

forecast quality. First, the SRBs are emptied continuously in the other control strategies during the investigated period, while in 'SRB CSO depth' and 'SRB MPC' the SRBs are emptied at a later time (14:00). Therefore, the SRBs are emptied by a rain volume of over 100 m^3, which causes a higher degree of filling of the CSO structure over the next hours. Consequently, these control strategies are more vulnerable to future precipitation, which is highlighted by an additional CSO event at 15:00 and higher duration and overflow volume at the second CSO event compared to the other control strategies. Second, for the model predictive control, the additional CSO event can be attributed to the forecast quality of the used weather forecasts. Additionally, Figure 5 shows the results of model predictive control applied with real weather forecasts in comparison to perfect weather forecasts, in which predicted amount and pattern illustrate exactly the real precipitation event. As can be seen in Figure 5(a), rain amount over the accumulation time of 4 h is nearly the same for real rain and real weather forecasts. However, there is a big difference in the time pattern noticeable. For the real weather forecasts, there is little precipitation predicted at the beginning, whereas the intensity is expected to increase strongly at the end of the forecast period. In contrast, the real event is divided into two precipitation periods with approximately equal amounts occurring in both first and second half of the forecast period. Consequently, if the control strategy 'SRB MPC' is tested with a perfect weather forecast, this additional CSO event can be avoided. In general, applying perfect weather forecasts further improves system performance as can also be seen in Table 3.

Illustration of flood performance

Figure 6 shows the performance for rain event 3 on 10 May 2018 in which the runoff exceeds the system capacity and flooding occurs. Total rain volume for this precipitation event amounts to 11.3 mm, whereas peak intensity is 1.3 mm/min at 15:24 (Figure 6(a)). In total, flood volume is 3.90 m^3 for the reference state without any RBs. As can be seen in Figure 6(b), nodes with flooding are mainly concentrated on one area in the middle of the sewer system,

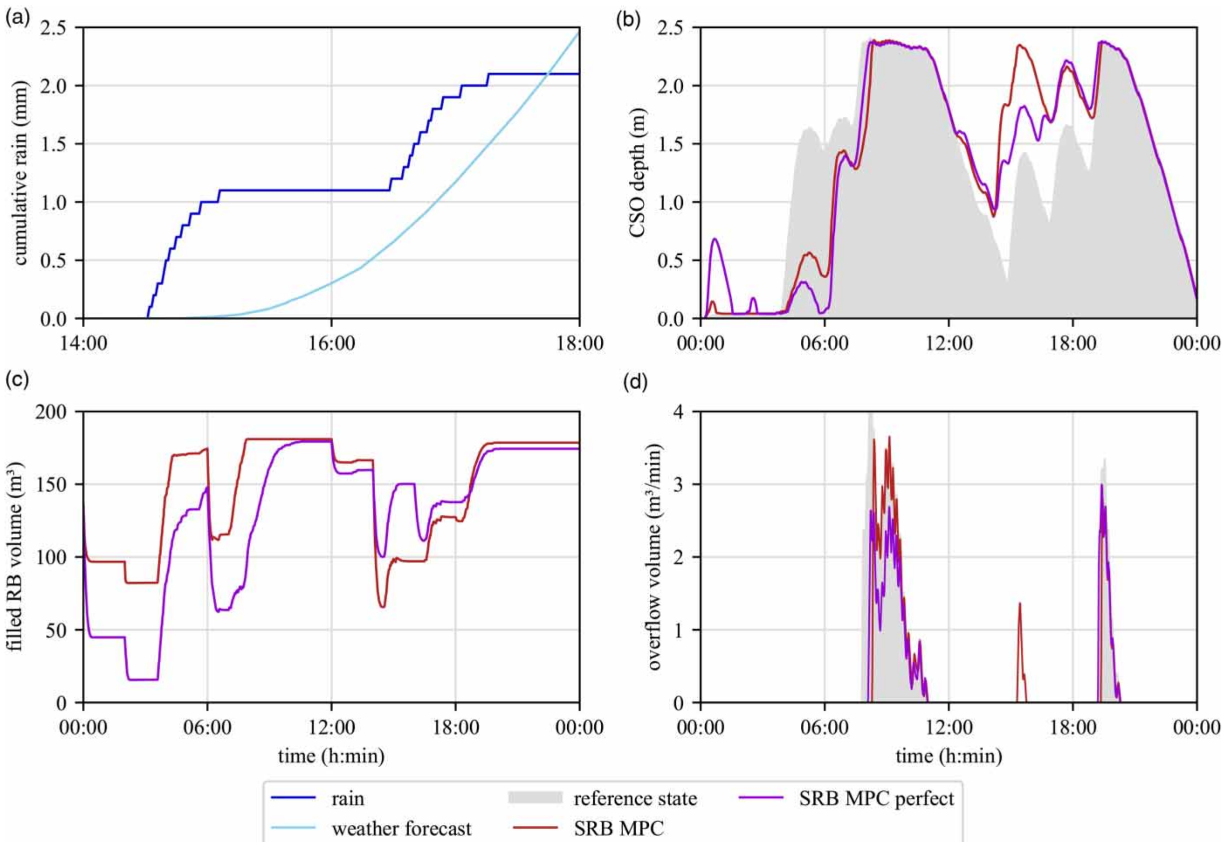

Figure 5 | Performance evaluation of 'SRB MPC' applied with perfect and real weather forecasts for the real rain event 2 on 29 March 2018.

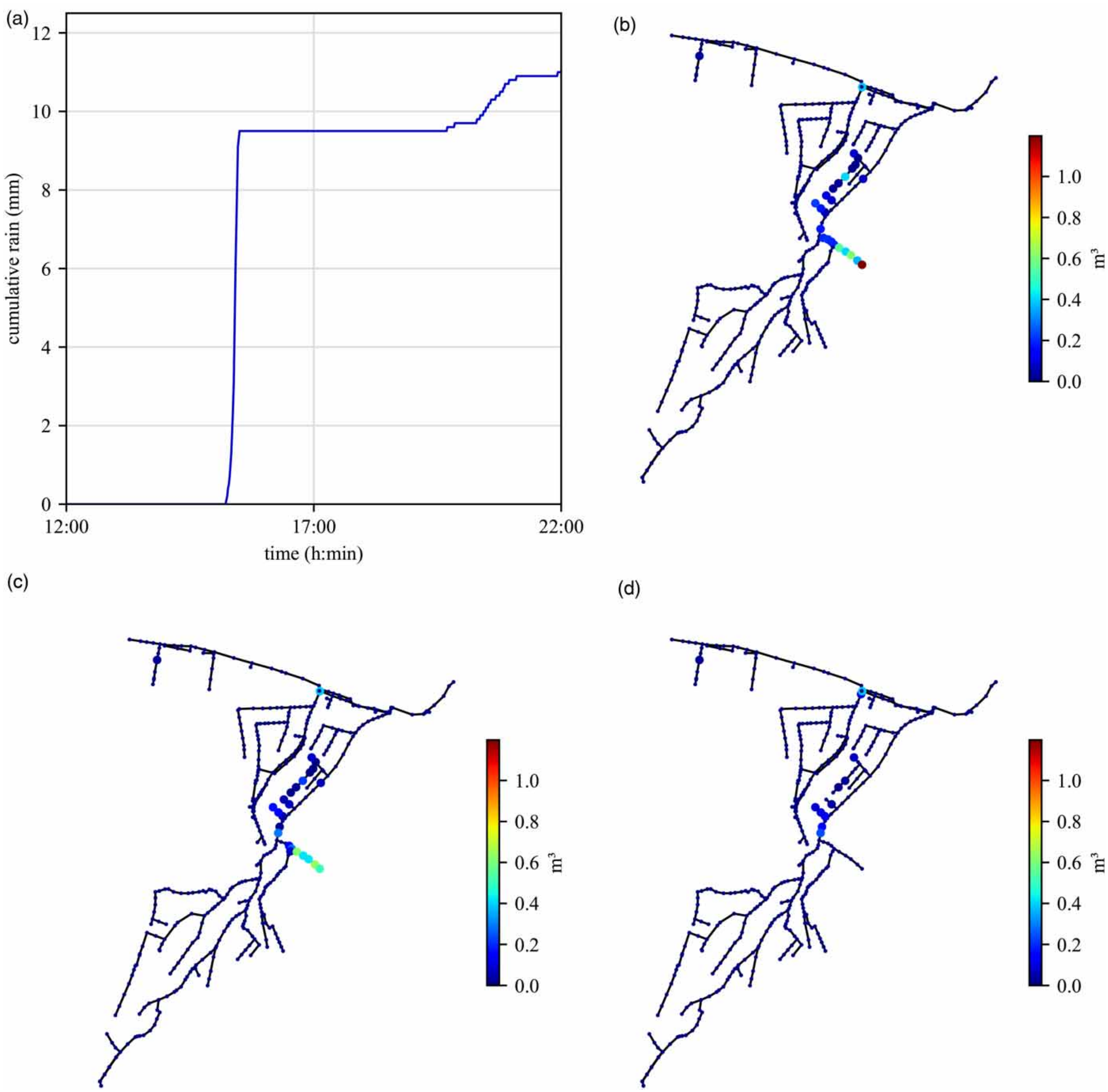

Figure 6 | Potential of the SRB concept to reduce flood volume for the real rain event 3 on 10 May 2018: (a) precipitation pattern, (b) flood volume of reference state without any RBs, (c) flood volume for control strategy 'SRB MPC' applied with real weather forecasts, and (d) flood volume for control strategy 'SRB MPC' tested with perfect weather forecasts.

which is characterised through low slopes in main and secondary pipes. In contrast, applying the SRB concept can reduce overflow volume. As an example, Figure 6(c) and 6(d) illustrate flood volume for the control strategy 'SRB MPC' applied with real and perfect weather forecasts, respectively. Therefore, real weather forecasts reduce mainly flood volume (reduction of 1.1 m^3), whereas perfect weather forecasts decrease both number of affected nodes and flood volume (reduction of 3.0 m^3).

Overall performance analysis

Figure 7 summarises the results of the investigated rain events including the summer half-year 2018 subdivided into the chosen performance indicators for wet weathers. As the results show, CSO reduction compared to the reference state without any RBs is between 7 and 67%. As expected, there is a difference between the applied control strategies noticeable. More advanced control strategies

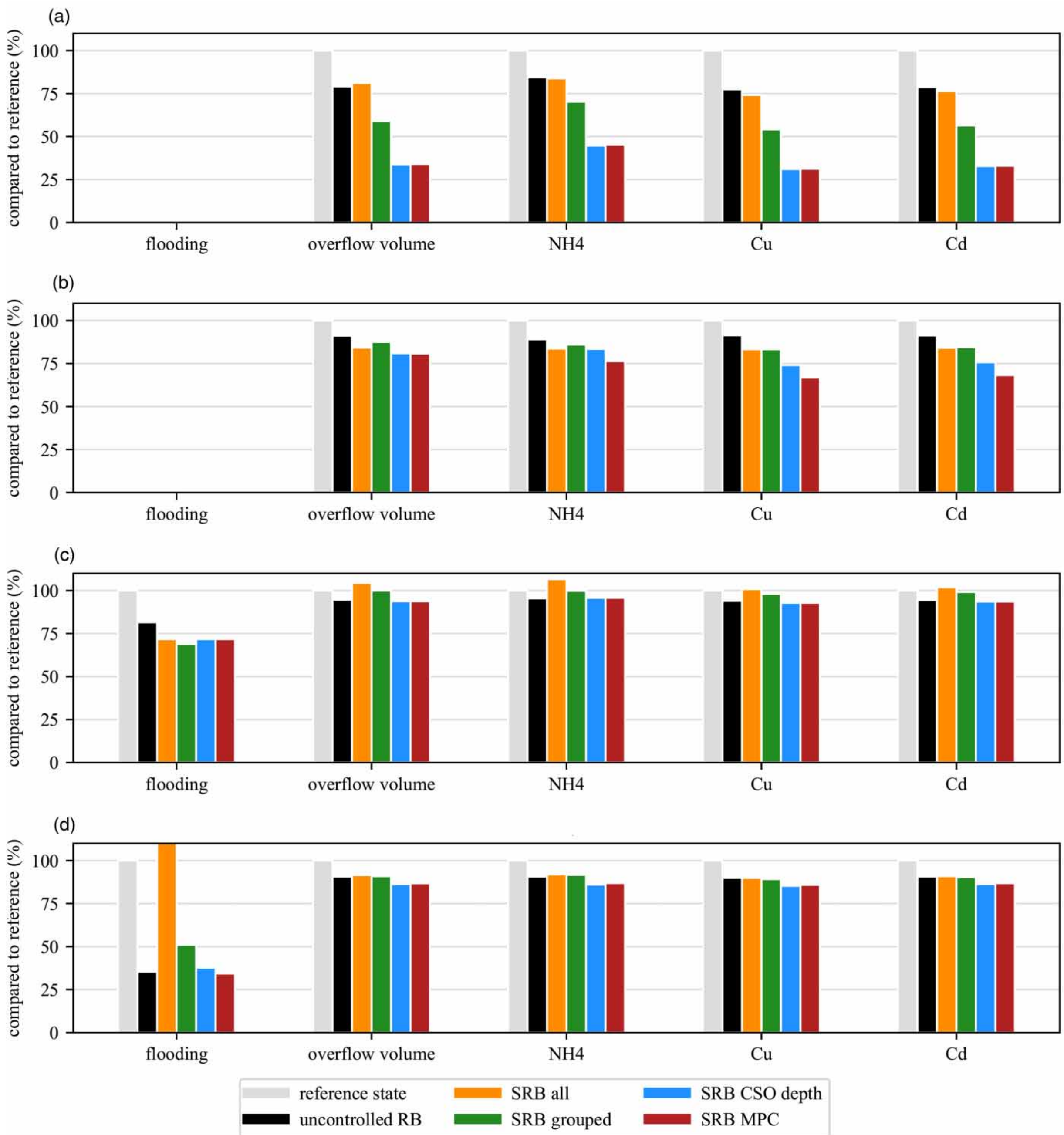

Figure 7 | Performance evaluation (reduction of volume/pollution mass) compared to the reference state of different control strategies for (a) rain event on 15 July 2018, (b) rain event on 29 March 2018, (c) rain event on 10 May 2018, and (d) summer half-year 2018.

including overall system states (e.g., 'SRB CSO depth' or 'SRB MPC') have a better performance than simpler strategies without considering sewer states for discharge events of the SRBs (e.g., 'SRB all' and 'SRB grouped'). Considering sewer states, e.g., filling depth of the CSO structure, prevents the SRBs from being emptied when conditions are unfavourable, thus reducing the risks of artificial CSO events. Additionally, in 'SRB MPC' number of discharge valves opened is optimised regarding CSO performance, therefore this control strategy achieves the highest CSO reduction of all investigated control strategies. In contrast, the control strategy 'SRB CSO depth' is based on a sensor measuring filling depth in the CSO structure. Interestingly, performance indicators show only minor differences to 'SRB MPC' for all investigated rain events. Consequently, by choosing a convenient threshold for discharge events of SRBs implemented, almost identical results can be achieved, while considerably less information (e.g., sewer network) is required for implementation.

As can be concluded from the results, effectiveness of the SRB concept is strongly dependent on characteristics of the rain events (e.g., amount of precipitation, rainfall pattern) and thereby caused CSO event. As the SRB concept implements micro storage, efficiency is particularly higher if CSO volume is in balance with implemented storage volume. However, the relationship between CSO volume and implemented additional storage volume decreases with higher overflow volumes, thereby reducing effectiveness. As can be seen from the investigated rain event 2 (Figures 3 and 7(b)), rain breaks during the rain event reduce the utilised system capacity (e.g., in this work filling depth of CSO structure), and can be used to empty the SRBs to provide additional storage volume. Consequently, the SRB concept is more effective than uncontrolled RBs if the SRBs implemented are already (partially) filled with rainwater due to previous precipitation.

As the EMC concept for predicting pollution loads is applied, reduction of pollution mass in CSO volume is strongly dependent on overflow volume. Interestingly, the effectiveness for Cu and Cd reduction is higher for the advanced control strategies compared to simpler strategies. For example, main sources for Cu are roof areas, which are also the catchment areas of the SRBs. Through a coordinated emptying of the SRBs based on sewer states, artificial CSO events caused by discharge of roof runoff can be avoided, which also decreases Cu mass in CSO overflow. In this context, a critical discussion about applied spatial and temporal resolution of pollution modelling cannot be missing. Due to the use of a finely subdivided simulation models, time and area type-dependent pollutant models are also required, however hardly any values (especially for heavy metals) at this level of detail are yet to be published. Therefore, using event mean-based concentration greatly simplifies data collection and allows a first assessment of the effects, but, conversely, also loses the dynamics of pollution wash-off (e.g., first flush effect). However, as the results indicated, the SRBs can postpone the start of a CSO event, thereby a further reduction of pollution mass is expected compared to EMC.

Further discussion and outlook

The main purpose of a rainwater harvesting system is to provide rainwater for non-potable water applications (e.g., irrigation, toilet flushing). The ability to release stormwater automatically can lead to a not fully filled RB at the end of each precipitation event in cases when more rainfall is forecasted that actually falls, thus decreasing the amount of substituted drinking water. Additionally, smart rainwater harvesting systems are strongly dependent on digital system components (e.g., accuracy of weather forecasts, reliability of data communication technology, effectiveness of control strategy), whereby disturbances can significantly impact the effectiveness in terms of stormwater detention and rainwater harvesting. Consequently, further analysis should pursue an integrated approach, including performance indicators of urban drainage network, rainwater harvesting systems and digitalisation. If all these factors are considered, the complexity of the control strategy is significantly increased, and opens up future research topics.

CONCLUSION

In this work, different control strategies for the SRB concept for wet weather are investigated. The SRBs are real-time controlled micro storages with a storage volume between 200 and 500 L and used for smart rainwater harvesting management. The SRBs are developed as an IoT-solution and can be emptied prior to rain events to increase detention volume. For the case study, a sewer system of an alpine municipality was utilised and 384 properties in land classified as residential area, mixed-use area, and agricultural area were hypothetically retrofitted with SRBs, providing an additional storage volume of 181 m^3. The simulations were performed with the open-source software 'Smartin', which can model micro storages developed as an IoT-based solution in a coupled model of urban drainage and water supply system.

Flood volume and combined sewer overflow (CSO) performance (e.g., overflow volume, ammonia (NH_4), copper (Cu), and cadmium (Cd) concentrations), are used as indicators to evaluate the effectiveness of control strategies applied for wet weather. The different control strategies are tested and evaluated by using three characteristic rain events of summer half-year 2018. Therefore, CSO volume and subsequently pollution mass is reduced between 7 and 67% depending on the control strategy and rain characteristics. As the results indicated, simpler control strategies (e.g., simultaneously or grouped opening of discharge valves of the SRBs implemented) create artificial runoff waves in the sewer and can therefore worsen system performance even above the reference state. It comes as no surprise, that more advanced control strategies (e.g., based on filling CSO, model predictive control), which take the actual sewer system into account, can better reduce the performance indicators and can thereby significantly improve system performance.

However, the effectiveness is strongly dependent on rain characteristics (e.g., rain pattern, amount of precipitation). For example, the tested control strategies are more effective with rain events interrupted with rain breaks. Rain breaks reduce the utilised system capacity and can therefore be used to empty the SRBs to provide additional detention volume. Consequently, the SRBs provide an advantage compared to uncontrolled RBs, if the storage volume is (partly) filled due to previous rain events. Additionally, the relationship between storage volume of the SRBs and CSO overflow volume is a major factor influencing effectiveness. As the SRBs provide only a limited additional detention volume, the effectiveness increases with lower CSO volume. If the available storage volume is filled with rainwater, no further improvements regarding CSO performance can be achieved. For higher CSO volume, the SRBs can postpone the start of an CSO event, which is important in the event of a first-flash phenomenon.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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