

Assessing the efficiency of different CSO positions based on network graph characteristics

R. Sitzenfrei, C. Urich, M. Möderl and W. Rauch

ABSTRACT

The technical design of urban drainage systems comprises two major aspects: first, the spatial layout of the sewer system and second, the pipe-sizing process. Usually, engineers determine the spatial layout of the sewer network manually, taking into account physical features and future planning scenarios. Before the pipe-sizing process starts, it is important to determine locations of possible weirs and combined sewer overflows (CSOs) based on, e.g. distance to receiving water bodies or to a wastewater treatment plant and available space for storage units. However, positions of CSOs are also determined by topological characteristics of the sewer networks. In order to better understand the impact of placement choices for CSOs and storage units in new systems, this work aims to determine case unspecific, general rules. Therefore, based on numerous, stochastically generated virtual alpine sewer systems of different sizes it is investigated how choices for placement of CSOs and storage units have an impact on the pipe-sizing process (hence, also on investment costs) and on technical performance (CSO efficiency and flooding). To describe the impact of the topological positions of these elements in the sewer networks, graph characteristics are used. With an evaluation of 2,000 different alpine combined sewer systems, it was found that, as expected, with CSOs at more downstream positions in the network, greater construction costs and better performance regarding CSO efficiency result. At a specific point (i.e. topological network position), no significant difference (further increase) in construction costs can be identified. Contrarily, the flooding efficiency increases with more upstream positions of the CSOs. Therefore, CSO and flooding efficiency are in a trade-off conflict and a compromise is required.

Key words | automated design, CSO positions, Virtual Infrastructure Benchmarking, virtual case studies

R. Sitzenfrei (corresponding author)

C. Urich

M. Möderl

W. Rauch

Unit of Environmental Engineering,

University of Innsbruck,

Technikerstr. 13,

6020 Innsbruck,

Austria

E-mail: robert.sitzenfrei@uibk.ac.at

INTRODUCTION

For urban drainage systems, there are in general two tasks: protection of human beings (hygiene, flooding, etc.) and protection of nature from anthropogenic impacts (emissions, etc.). The technical design of drainage systems has to be performed in a predictive way, taking into account, among other things, statistical evaluation of rain data and return periods (Arnbjerg-Nielsen 2011), future developments of the urban areas (Doglioni *et al.* 2009), climate change effects (e.g. Kleidorfer *et al.* 2009; Mailhot & Duchesne 2010), but also following technical principles such as ensuring hydraulic functionality under different conditions, safety and cost-effectiveness, regarding construction and operation (Butler & Davies 2004). With these principles, the technical design of urban drainage systems is specified to protect nature

from human beings and vice versa in an economical maintainable way. In addition, more recently the issue of sustainability and preserving the natural urban water cycle has become more important in the design and retrofit of urban drainage systems (Ole *et al.* 2012; Stovin *et al.* 2012).

The technical design of urban drainage systems comprises two major aspects: first, the spatial layout of the sewer system and second, the pipe-sizing process (Haghighi 2012). Usually, engineers take into account physical features (areas to drain, connections to existing pipes, available spaces for sewer pipes, etc.) and future planning scenarios to manually determine the spatial layout of the sewer network. Before the pipe-sizing process starts, it is important to determine locations of weirs and possible combined

sewer overflows (CSOs) based on, e.g. distance to receiving water bodies or to a wastewater treatment plant (WWTP) and available space for storage units.

The planning task for a combined sewer system (CSS) is not a green-field approach (Butler & Davies 2004). To drain new areas, new sewers are connected to an existing sewer system. Nevertheless, in order to better understand the impact of placement choices for CSOs and storage units in new systems but also for existing systems, this work aims to determine case unspecific, general rules for alpine systems. Therefore, based on 2,000 stochastically generated virtual alpine sewer systems of different sizes (Urich *et al.* 2010), it is investigated how choices for placement of CSOs and storage units have an impact on the pipe-sizing process (hence, also on investment costs) and on technical performance (CSO and flooding efficiency). Although the investigations are based on systems with alpine characteristics, the proposed method is also applicable to other kinds of regions. To describe the impact of the topological positions of these elements in the sewer networks, graph characteristics are used.

METHODS AND MATERIALS

In research, investigations are often based on a limited number of case studies. Therefore, the obtained results from such investigations are case specific. The aim of this study is to obtain more case unspecific results. For that, a set of automatically generated virtual (synthetic) test cases for CSSs are used. The used set of CSS is created with the VIBe (Virtual Infrastructure Benchmarking) approach. For the topological network analysis, the CSSs are characterized with the graph theoretical 'Strahler number' (Strahler 1952) which is usually used to describe river streams. Based on the 'Strahler number' adapted for CSS (sewer branch order (SBO)), an automatic pipe-sizing and CSO design is applied. The geometrical properties (pipe diameters, storage volumes, etc.), the costs and the technical performance for each investigated CSS are determined. The described approach is applied to 2,000 CSSs created with VIBe. The scenario definition and characteristics of these 2,000 CSSs are finally discussed.

Test cases – VIBe

In this work the VIBe approach is used to automatically generate numerous urban water systems with different characteristics for case study analysis. With that approach,

city scale case studies including geographic information system (GIS) data for urban structure and network data for water infrastructure are created and can be used for further investigations. As a result of the generation procedure with VIBe, input files for simulation software are automatically created and can be used for hydraulic analysis. The generation process for the used test cases is split up into two modules. The 'urban structure module' generates the city layout and the 'sewer module' generates the corresponding CSS. To generate cities with the 'urban structure module', input parameters for the urban environment are required. For alpine cities, these input parameters were determined in Sitzenfrei *et al.* (2010). The 'urban structure module' basically generates GIS data which are further used by the infrastructure modules or for GIS-processing. The generated data is mainly raster based data (organized in data layers). A raster resolution of 20 m was chosen for all data layers. This choice was made in order to allow representing structures like streets but also in regard of the amount of data (computer capacity). Therefore, with this resolution, the modelling aim (basically, to create urban drainage with accurate level of detail) can be achieved. In the sewer module of VIBe, agent based modelling techniques are used, in order to combine flow routing (basically driven by gravity) from hydrology with technical urban drainage principles. In the context of finding a sewer layout based on GIS data from the 'urban structure module', the movement paths of agents represent water ways (sewer pipes) of urban drainage. Therefore, it is a flow routing which is not only driven by gravity, but also by technical design guidelines (vertical alignment, sewer slopes, least cost design, etc.). The agents mark the path of their movement and therefore, after applying several generations of agents, possible sewer layouts are obtained (Urich *et al.* 2010). Due to the generation procedure the CSSs are fully branched.

'Sewer branch order' and CSO positions

The 'Strahler stream order' (Strahler 1952) mathematically describes the branching complexity of a branched river network. In this work the 'SBO' is used both to describe the network topology (Urich *et al.* 2010) and for positioning of CSOs. For each of the generated sewer network layouts, different strategies based on SBO (i.e. placement of CSOs at specific SBO) are investigated to determine efficient locations for CSOs.

All pipes from starting nodes (in terms of a CSS, most upstream inlet nodes) are defined with a SBO of 1.

Subsequently, going downstream, the order of all pipes is defined with the following two rules:

1. If two or more pipes with the same order i join, the SBO of the next downstream pipes is $i + 1$.
2. If two or more pipes with different orders join (i, j and $i < j$), the next downstream pipe has the higher of the two SBOs (in this case j).

To describe the order of a junction i , the upstream-connected maximum SBO_i is used. In Figure 1, left, the SBO is applied to an example CSS.

S_{\max} indicates the highest SBO_i in a CSS (in Figure 1, $S_{\max} = 3$). The different CSO strategies dS_i take into account the difference between the actual SBO_i in a pipe i and the highest one in the system S_{\max} . Or, in other words, the difference between the actual SBO_i and S_{\max} is referred to different CSO strategies dS_i ($dS_i = S_{\max} - SBO_i$). A CSO strategy of dS_i means that at every upstream end of a pipe with $SBO_i = S_{\max} - dS_i$ a CSO is placed. In Figure 1, $dS_i = 0$ and $dS_i = 1$ is used for CSO strategy I and CSO strategy II, respectively. For example, for CSO strategy II (Figure 1 right), at every upstream node of a pipe i with $SBO_i = 2$ ($S_{\max} - dS_i = 3 - 1$) a CSO is placed. In this example, there are three pipes with $SBO_i = 2$ and therefore three CSOs are placed at the upstream ends of these pipes. A lower dS_i results in fewer CSOs downstream and more in upstream positions. For the investigations in this work the CSO strategies $n = 0, 1, 2, 3$ and S_{\max} are investigated.

Pipe-sizing and design of CSOs and storage units

For the pipe-sizing algorithm in the sewer module of VIBE, the time area method is used (Butler & Davies 2004). To place the CSO structures, the SBO was used to determine locations (Urich et al. 2010). In practice, CSOs often have a complex structure and cannot be described with simple equations (e.g. Fach et al. 2009). Anyhow, in this work

simple side weirs are used with a weir length of 8 times the inlet diameter (d_i) and a weir height of $0.9 \cdot d_i$. For an overflow coefficient $k_w = 0.5$ (Fach et al. 2009) is used which results in $C_w = 1.48$ as a parameter in SWMM (Rossman 2004). The design of nodal storage volume and the sewer network is according to Austrian national standard (ÖWAV-RB 1987), which is valid for design of single CSO structures. With the impervious area (A) in hectares (1 ha = 10,000 m²) the minimum required hydraulic flow capacity, i.e. the throttle flow (Q) in order to transport combined wastewater to the WWTP can be determined with $Q = 15 A$ (l/(s ha)) and the required storage volume (V) is calculated with $V = 15 A$ (m³/ha). A minimum volume of 50 (m³) is regarded.

Sewer cost model

In this study, only total construction costs are evaluated (no operation costs). The specific construction costs for sewer and storage units are estimated according to HMULV (2011). For diameters (DN) below 200 (mm) specific construction costs (C_P) of 330 (€/m) are assumed and for diameters above 1,400 (mm) 1,290 (€/m). In between, linear interpolation applies with C_P (€/m) = 800 DN (m) + 170. The specific construction costs for sewers are estimated independent from depth of installation. The specific construction costs of storage volume (C_s) are estimated with 665 (€/m³) for volumes below 500 m³ and 360 (€/m³) above 2,000 (m³). For volumes (V) in between it is interpolated with C_s (€/m³) = 10,234 V (m³)^{-0.44}. The total construction costs (C) are estimated as the sum of specific sewer construction costs for different sections ($C_{P,i}$) times lengths of sewer sections l_i (p sections) and specific storage unit constructions costs for different structures ($C_{s,j}$) times actual storage volume V_j (n structures):

$$C(\text{€}) = \sum_{p=1}^{i=1} C_{P,i} \cdot l_i + \sum_{n=1}^{j=1} C_{s,j} \cdot V_j. \quad (1)$$

Performance assessment

For assessment of technical performance of the entire system, the impact of CSO placement strategies on flooding and emissions (CSO efficiency) are evaluated. As hydraulic solver, SWMM5 is used (Rossman 2004) with an event based design storm event of type EULER II (ATV-A n8E 2006) with a return period of 5 years and a rain duration of 2 hours. The used CSO efficiency (P_c) for the entire system is derived from the Austrian standard (ÖWAV-RB

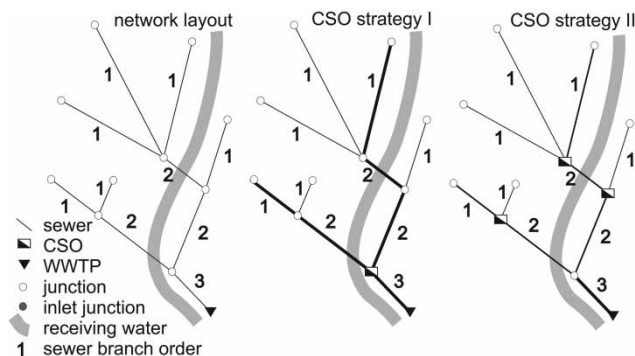


Figure 1 | 'SBO' and CSO placement strategies applied to an example CSS.

19 2007; an English description is available in Kleidorfer & Rauch 2011) applied for a single rain event, and not for a long term rain series, in order to obtain a reasonable computation time. It is calculated as the ratio between volume of surface runoff which is transported to the WWTP and total surface runoff. A CSO efficiency of one indicates that the entire surface runoff is treated at the WWTP. For a long time series, the Austrian standard requires a CSO efficiency depending on system size and rain characteristics between 0.4 and 0.6. To estimate flooding efficiency (P_F) one minus the maximum ponded volume over all nodes is divided by the total rainfall runoff volume (Möderl et al. 2009). A flooding efficiency of one indicates that no flooding event occurs.

Scenario definition and characterization of the test cases

For test cases, 200 city layouts are generated with VIBE (Sitzenfrei et al. 2010). Populations of the 200 generated city layouts range from 6,000 to 150,000 with sewer lengths between 12 and 90 (km) (see Figure 2, left). For each city layout, a CSS is automatically created (Urich et al. 2010). Each of the resulting CSSs is subsequently used to test different CSO design strategies ($dS_i = 0, 1, 2, 3, S_{max}$).

In addition, the storage volume is distributed at different positions in the systems. In the 0th scenario the entire storage volume is at the WWTP (dash-dot lines in Figure 2, right, 'no V' in the legends) and as an additional scenario, at each CSO a storage unit is placed with a volume according to the design guidelines described above ('with V' in legends). In Figure 2, right, the empirical cumulative distribution functions of the investigated test cases are shown with colours according to the CSO design strategies and

line styles according to the distribution of the storage volumes in the system.

These variations result in 10 different design scenarios for each of the 200 CSSs and 2,000 investigated systems in total.

RESULTS AND DISCUSSION

In the following, the characterized 2,000 test cases are evaluated and discussed. In Figures 3–5 each marker (dot or x) indicates the result of one test case. Figure 3 left shows the storage volumes of the different test cases plotted versus the flooding efficiency (P_F). For P_F a sufficient threshold value of $P_F \geq 0.9$ is assumed. The choice of that threshold is based on evaluations of a real world alpine system (Urich et al. 2010). For example, for optimization strategies, a change of that value might be required but it has to be determined in relation with the chosen return period of the design storm event.

The legend of Figure 3 left also indicates the fail rate (i.e. P_F below 0.9) of the different strategies. It can be seen that for $dS_i \geq 2$ the flooding performance is more likely to be sufficient (8%, 3% respectively less than 1% of these systems have a flooding efficiency below the threshold value of $P_F < 0.9$). For $dS_i < 2$ also with high storage volume a sufficient P_F is not necessarily achieved (dots and x below P_F of 0.9). For example, for the CSO strategy $dS_i = 0$, 20% of the investigated systems have an insufficient P_F . Based on these investigations, a CSO strategy of $dS_i \geq 2$ is preferable.

Figure 3, right, shows the CSO efficiency of the systems (P_C) versus the flooding efficiency (P_F). It can be observed that for an insufficient P_F maximum, a similar value is

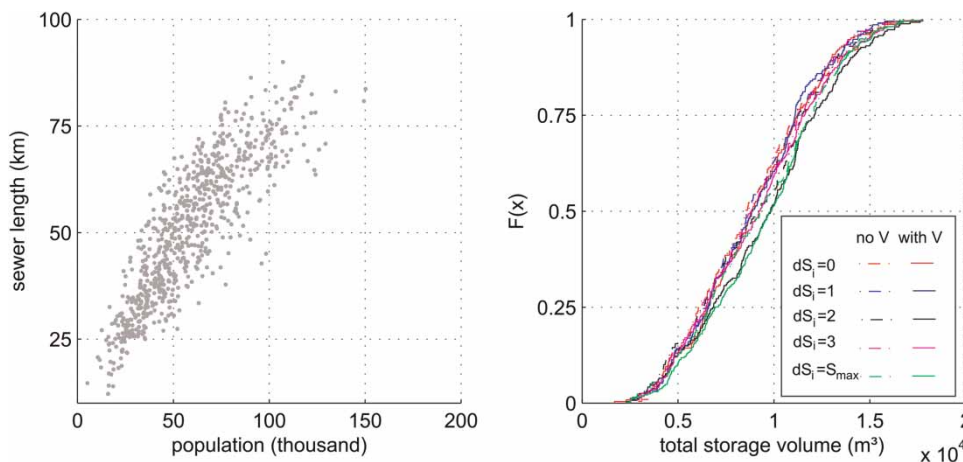


Figure 2 | Characterization of the test cases and scenarios (the full colour version of this figure is available in the online version of this paper, at <http://www.iwaponline.com/wst/toc.htm>).

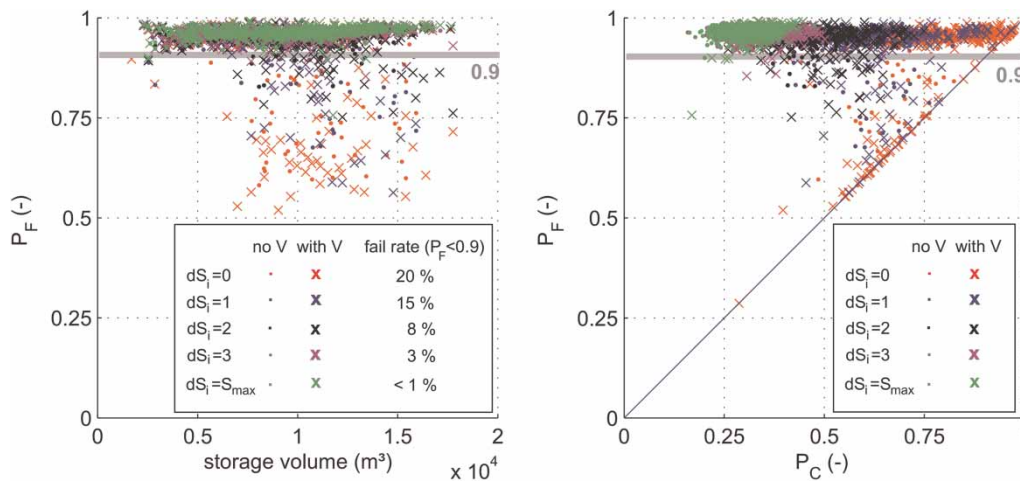


Figure 3 | Hydraulic performance of test cases and scenarios.

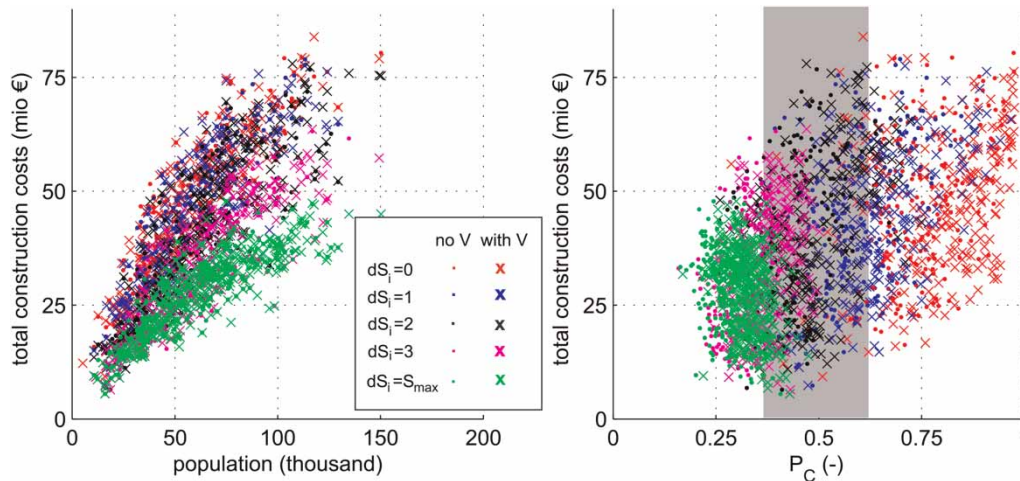


Figure 4 | Total construction costs depending on population and CSO efficiency.

obtained for P_C (i.e. there are no markers below the line $P_F = P_C$). This is due to the definition of the two performance indicators and the chosen simulation option in SWMM5 by which no flooded volume flows back in the CSS. Because of a high amount of flooded volume (low P_F), less water can be transported to the WWTP. Therefore, the maximum possible ratio between water treated at the WWTP and total rainfall runoff volume also decreases. With statistical evaluations, no significant difference between the strategies for allocation of storage volume (Figure 3, different markers) can be observed.

In Figure 4, the total construction costs (C) for different populations and CSO efficiencies (P_C) are shown. Again, for both plots in Figure 4, no difference between the strategies for allocation of storage volume (different markers) can be

identified. A higher dS_i results in lower construction costs due to more CSOs in the systems. For $dS_i \leq 2$, no significant difference (further increase) in construction costs can be identified even though there is an increase in CSO efficiency (P_C in Figure 4, right). This indicates that a CSO placement strategy of $dS_i \leq 2$ would be preferable regarding CSO efficiency and total construction costs. However, the technical performance regarding shear stress in terms of dry weather flow (low flow conditions) has not been taken into account in the assessment. A consideration of that can result in insufficient performance in low flow conditions for large circular pipes in cases where only a low number of CSOs are placed downstream.

To put the obtained results in context with the guidelines requirements, in Figure 4 right the grey background

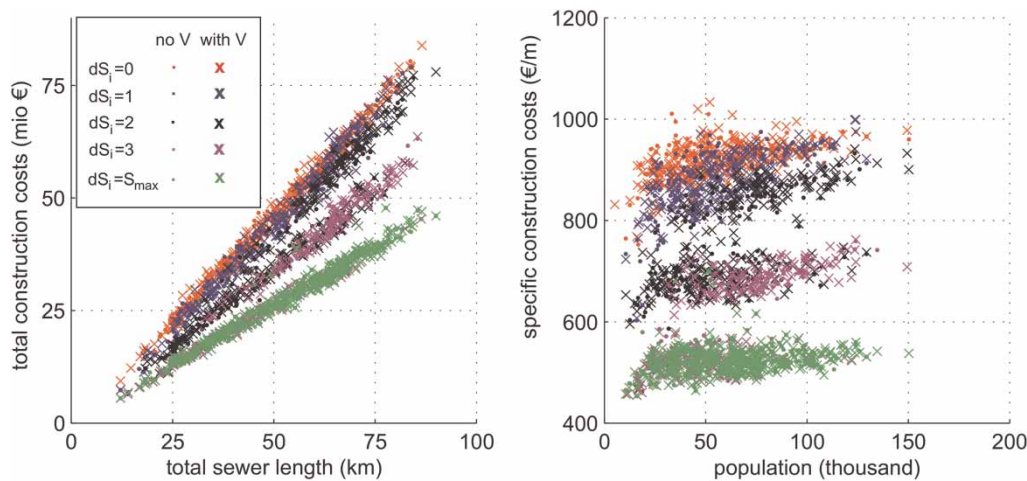


Figure 5 | Total construction costs depending on total sewer length, specific construction costs depending on total population.

indicates the required CSO efficiency according to the Austrian standard for a long time rain series of at least 10 years and different boundary conditions (ÖWAV-RB 19 2007). To reduce computation time, in this work a single design storm event with a return period of 5 years is used which underestimates the CSO-efficiency compared to a long time rain series (Kleidorfer et al. 2009). For $dS_i \geq 3$ the CSO efficiency is therefore insufficient. With decreasing CSO strategies, the CSO efficiency increases. Also, the total construction costs increase. In combination with Figure 4 left, it can be observed that for $dS_i \leq 2$, the total construction costs do not further increase. Therefore, in regard to total construction costs and CSO efficiency, a CSO strategy of $dS_i \leq 2$ is preferable.

In Figure 5 the total construction costs (mio €) and the specific construction costs (€/m) are plotted versus total sewer length and total population, respectively. The lower dS_i , the more expensive are the total and specific constructions costs. In both plots (Figure 5, left and right) at least a trisection of the data points can be observed. This corresponds with different levels of S_{max} and different sizes of the generated networks.

Again for both plots in Figure 5, no difference between the strategies for allocation of storage volume (different markers) can be identified. Anyhow, the centralized storage volume close to the WWTP has the advantage that in case of a distributed rainfall the volume can always be utilized. Especially in big systems, this is an important issue. The obtained results in this study show that no effect in terms of construction costs and hydraulic performance can be observed. Therefore, the strategy of a centralized (close to the WWTP) storage volume is encouraged.

For flooding efficiency, a CSO strategy of $dS_i \geq 2$ is preferable. This results in a high number of single CSOs at upstream positions in the network. For CSO efficiency and total construction costs, as well as specific construction costs, a CSO strategy of $dS_i \leq 2$ is preferable. This results in a small number of CSOs on downstream positions in the network. Therefore, flooding efficiency and CSO efficiency are facing a problem of trade-off. As a compromise, based on the evaluations in this work, a CSO strategy of $dS_i = 2$ moderately meet the requirements of both flooding and CSO efficiency.

SUMMARY AND CONCLUSIONS

In this work, it is investigated how CSOs at different topological positions in CSSs have an impact on hydraulic performance (CSO efficiency and flooding efficiency) and total construction costs. Two hundred different layouts of CSSs as test cases and 10 different CSOs and storage unit placement strategies in a total of 2,000 different CSSs with sewer lengths between 12 and 90(km) are investigated. The SBO is used for different CSO placement strategies and allocation of storage volumes.

For flooding efficiency, it was observed that with a high number of single CSOs in upstream positions, the systems are more likely to perform sufficiently. CSOs at downstream positions in the network result in higher construction costs and better performance regarding CSO efficiency. Anyhow, at a certain SBO, no significant difference (further increase) in construction costs can be identified even though there is an increase in CSO efficiency. This indicates that a

CSO placement strategy beyond this point would be preferable. Based on the evaluations in this work, a CSO strategy which moderately meets the requirements of both flooding and CSO efficiency based on graph characteristics of the sewer graph (SBO) was identified.

Further, it was observed that the simulation option in SWMM by which the ponded volume does not flow back into the sewer system has a major impact on CSO efficiency. Especially for event based simulations (e.g. for design storm events with return periods where a significant amount of water is ponded in the system), this effect is even more relevant.

In general, the hydraulic performance for different allocation strategies of storage volumes was comparable for these particular virtual alpine case studies. Therefore, because of the obtained results in this study that no effect in terms of construction costs and hydraulic performance can be observed for storage allocation, the strategy of a centralized (close to the WWTP) storage volume is encouraged, so that in terms of spatial distributed rainfall events, all the storage volume can be utilized in every case.

Further work focuses on describing also partly looped systems with a similar concept as the SBO in order to apply the obtained results to real world systems. In addition, more complex placement strategies based on connected impervious areas, distance to receiving water bodies, etc. will be taken into account.

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