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Impact of a changing environment on drainage system performance

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Abstract

Pavement of the surfaces, along with a possible climate change induced increase of rainfall intensities, is one of key factors accountable for (increased) flooding in urban areas. Consequently higher runoffs have an impact on sewer system performance in terms of higher risk of flooding and decrease of storm water treatment performance. This paper presents a sensitivity analysis to compare impact of increased rainfall intensities and pavement of urban areas. It can be seen that both impacts result in a similar figure. Hence it is important to look into both aspects when trying to predict future performance of combined sewer systems.

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Keywords: combined sewer system, climate change, land-use change, DynAlp

1. Introduction

Urban drainage systems are an important part of city infrastructure which have drawn public attention due to some severe flooding of the urban environment. Pavement of the surfaces, along with a possible climate change induced increase of rainfall intensities, is one of key factors accountable for (increased) flooding in urban areas (Grum et al., 2006; Semadeni-Davies et al., 2008; Arnbjerg-Nielsen and Fleischer, 2009). For example Nie et al. (2009) evaluated possible impact of climate change (3 scenarios of increased rainfall intensities of +20%, +30%

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and + 50%) on different sewer system performance measures including surface flooding and combined sewer overflow (CSO) and observed "dramatically" increase of flooding volume. Additionally previous studies have shown that on-going urbanization puts more and more pressure on existing drainage systems. Connecting new areas to existing sewer systems increases surface runoff and consequently runoff in pipes and discharge to receiving waters (Kleidorfer et al., 2009). Consequently higher runoffs have an impact on sewer system performance in terms of higher risk of flooding and decrease of storm water treatment performance. Planners have to account for these changes in future sewer system maintenance and replacement (Ashley et al., 2005).

As future conditions are uncertain, the assessment of the dynamic development of both cities and society is expected to be the key for successful infrastructure management. One possibility for adaptation is to disconnect paved urban areas from drainage systems to implement on-site treatment as stormwater infiltration facilities. To respond to the changes, continuous adaptation of the infrastructure is necessary by combining different technological solutions (e.g. on-site treatment, increase of pipe-sizes etc.). To reduce costs, adaptation of pipe networks should reasonably occur in line with the regular renewal/rehabilitation of aging infrastructure. Hence dynamic adaptation is crucial to maintain the drainage system operational.

Both impact of climate change and impact of city growth (leading to pavement of urban areas) is addressed in the research project DynAlp (Dynamic Adaptation of Urban Water Infrastructure for Sustainable City Development in an Alpine Environment). The first step (shown in this paper) is a sensitivity analysis to compare the impact of increased rainfall intensities (climate change impact) and pavement of urban areas (urbanization and land-use change). The system performance is represented by ponded volume during rainfall events, discharge of combined sewer overflows (water quantity) and discharge to receiving waters of total suspended solids loads and ammonium nitrogen loads.

Nomenclature

CCF	climate change factor
CSO	combined sewer overflow
EIF	effective impervious area
f_A	area factor
NH4-N	ammonium nitrogen
RP	return period [1/a]
TSS	total suspended solids
V_{CSO}	combined sewer overflow volume
V_{Flood}	Flooded (ponded) volume

2. Methods

2.1. The approach in the Project DynAlp

The project 'Dynamic Adaptation of Urban Water Infrastructure for a Sustainable City Development in an Alpine Environment (DynAlp)' focuses on city development and the potential impact of climate change on the adaptation and development of urban water infrastructure and addresses the aspect of pluvial flooding risk in detail. The aim of this project is to develop and apply a software framework that integrates urban development, climate change projections and drainage infrastructure adaptation. The novelty of this approach lies in an integrated consideration of climate change and urban development in a dynamic temporal scale. This means that not only future target grids of drainage networks are evaluated but also the pathway (in yearly timesteps) to reach that target grid. This enables us to test different adaptation strategies and to identify potential failure points in that pathway. The first step of this project is a sensitivity analysis to assess potential impact of climate change induced increase of rainfall intensities and impact of land-use change.

2.2. Case study Innsbruck and model description

The case study shown is characterized by Alpine climate conditions (cold winters and summers with intense rainfall). The city is drained in a combined system, so rainwater is either treated at the waste water treatment plant or discharged to the receiving water. The total catchment area is about 2.028 ha, whereas 745 ha are impervious (i.e. the average fraction imperviousness is 0.37). This sewer system is modeled as a fine-grained combined sewer network consisting of 5358 nodes, 4528 sub-catchments, 5695 links and 53 outfalls. The entire system drains to a central waste water treatment plant (see Fig. 1).

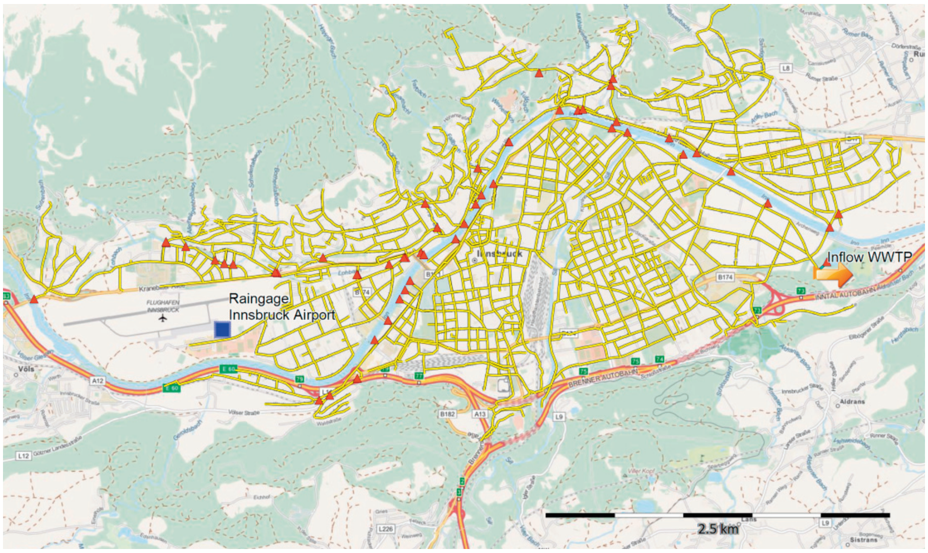

Fig. 1. Model of the sewer system of Innsbruck (Visualization in software PCSWMM; background: Open Street Map)

2.3. Performance assessment

This work is based on hydrodynamic computer simulations of combined sewer systems. The model used in this study is the well-known hydrodynamic model SWMM 5.0 (Rossman, 2008). Hence the impact on flooding and surcharge as well as on combined sewer overflow (CSO) discharge to the receiving water can be analyzed. The rainfall/runoff model has been calibrated on water-level measurements at the CSO structured. Water quality is calculated using a simplified approach with constant pollutant concentrations for dry-weather and rainwater runoff. These concentrations are chosen according a large urban runoff pollutant database (Brombach et al., 2005).

The performance of the system is assessed by means of ponded (flooding) volume leaving the system (V_{Flood} measured in m^3), CSO discharge (V_{CSO} measured in m^3), discharge of total suspended solids load (L_{TSS} – measured in t) and discharge of ammonium nitrogen load ($L_{NH4\text{-}N}$ measured in tons). These performance indicators were chosen because they can be used the express system-wide performance (in contrast to values which have to be calculated for each pipe as for example flow peaks).

2.4. Sensitivity to a changing environment

To investigate the sensitivity of the system response to changes of rainfall-input (climate change effect) and fraction imperviousness (land-use change and city growth) in this paper a modeling study with varying boundary conditions is shown. Therefore both rainfall input and sub-catchment characteristics are changed and the impact on the performance indicators is evaluated and compared.

2.4.1. Rainfall events and climate change

For this analysis only selected single rainfall events – extracted from 14 years of continuous measurements – are chosen. Therefore the rainfall records of a rain gauge within the catchment (see Fig. 1) are analyzed and evaluated statistically. We evaluated intensity duration curve and the average intensity of the long-time series over 15 and 60 minutes for different return periods (RP=1, RP=2, RP=3 and RP=5) as these are typical values to characterize rainfall events. The 15 minutes and the 60 minutes intervals have been chosen to account for both flooding and CSO discharge performance. Subsequently we selected those measured rainfall events, which contain the evaluated rainfall intensities (see Table 1). Rainfall events here are defined as independent if separated from each other by a dry-weather period of at least one hour. The rainfall time-step is 5 minutes.

Table 1. Characteristics of selected rainfall events: rainfall characteristic R with interval (min) and return period (RP); duration of the event, sum of rainfall volume (mm) and intensity peak (mm/5min).

Event ID	R min,RP	Duration [hh:min]	Sum [mm]	Peak [mm/5min]
1 4	r15,1	01:05	12.9	6.3
2 3	r15,2	00:30	13.3	7.3
3 2	r15,3	13:05	20.3	6.5
4 1	r15,5	01:05	23.9	7.8
5 8	r60,1	17:15	16.3	3.3
6 7	r60,2	02:20	31.2	5.1
7 6	r60,3	01:05	25.7	4.8
8 5	r60,5	01:30	23.9	7.8

Arnbjerg-Nielsen (2008) calculated climate factors for consideration of climate change in design of urban drainage systems for Denmark based on three different approaches. He estimates the increase in design intensities by 10 – 50% depending on duration, return period and anticipated technical lifetime of sewer systems. Although this climate change factor (CCF) varies regionally (De Toffol et al., 2006) that bandwidth of 10-50% is assumed and analysed in this study in steps of 10% (CCF=1.0; 1.1; 1.2; 1.3; 1.4; 1.5). Consequently for each 5 min timestep j the rainfall intensity under consideration of climate change conditions $I_{CCF,j}$ is calculated from original rainfall intensity I_j multiplied with the climate chance factor CCF.

2.4.2. Land-use change

The land use change is simulated again straightforward as change in the imperviousness of the system. However, these changes can be either (numerical) positive (e.g. due to new developments that lead to an increase of paved areas) or negative due to rainwater infiltration or harvesting (Mair et al., 2012; Mikovits et al., 2013). Due to this aspect the bandwidth of this parameter is varying from -40% and +60%. Hence effective impervious area (*EIF*) for future conditions is calculated from current conditions and an area factor f_A (f_A=1.0; 1.2; 1.4; 1.6; 1.8) for an increase of paved area and for a reduction of paved area according, respectively, to:

$$EIF_{f_A} = EIF \cdot f_A \qquad (1)$$

$$EIF_{f_A} = EIF \,/\, f_A \qquad (2)$$

Consequently in total 432 scenarios (8 rainfall events x 9 climate scenarios x 6 land-use scenarios are calculated and evaluated statistically.

3. Results and discussion

3.1. Simulation results

Fig. 2 shows the simulation results for the current condition. As can be seen, in general, the system performance decreases (i.e. ponded volume and discharges increase) - as expected – with higher return periods of the rainfall events (i.e. from event 1 to 4 and from event 5 to 8 – see Table 1). However, due to the dynamics of the rainfall events this effect is not as straightforward for CSO discharges (both water quantity and pollutant loads) as it seems. For example CSO discharges decrease from event 6 (RP=2) to event 8 (RP=5).

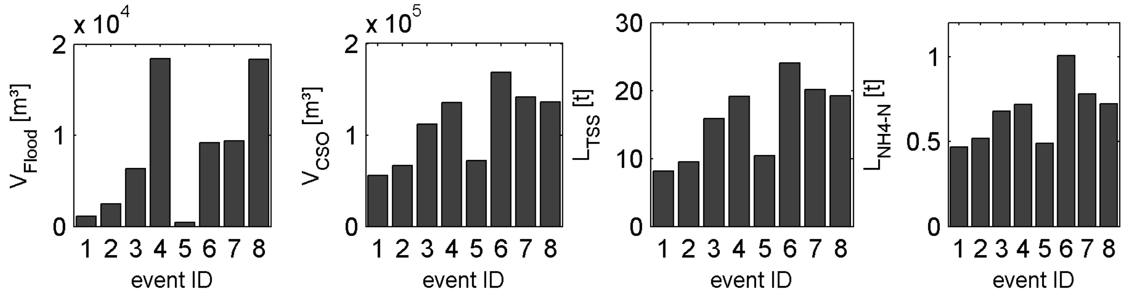

Fig. 2. Simulation results for the current system: (a) ponded volume (m^3); (b) CSO discharge (m^3) ; (c) TSS discharge (t); (d) NH4-N discharge (t)

3.2. Impact of climate change and land-use change

3.2.1. Climate change

Fig. 3 shows the impact of increased rainfall intensities (expressed as CCF) on system performance for the eight rainfall events. As can be seen the ponded volume increases dramatically. The highest increase (>1000% for CCF=1.5) can be seen for rainfall event 5 (RP=1) which increases from a relatively low ponded volume of 1,140 m³ to 12,976 m³. For the rainfall events representing RP=5 (events 4 and 8) ponded volume increases by approximately 430%. The increase of CSO and pollutant discharges is much less (always being well below 100%). Here it is interesting to see, that impact of increased rainfall intensities is similar for all rainfall events and all return periods.

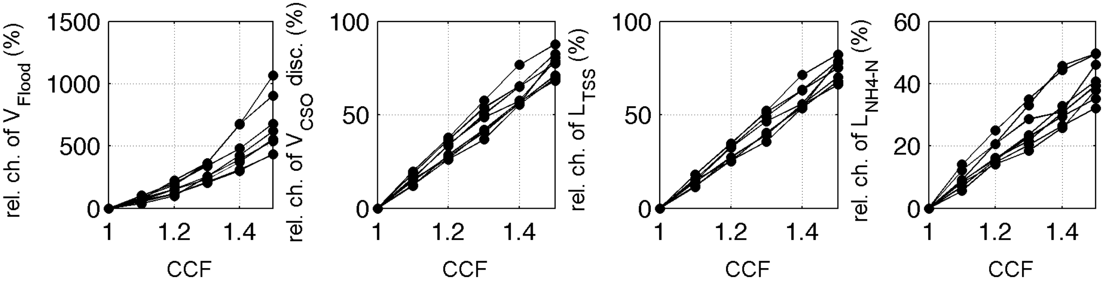

Fig. 3. Impact of rainfall intensities on (a) ponded volume (m^3); (b) CSO discharge (m^3); (c) TSS discharge (t); (d) NH$_4$-N discharge (t)

3.2.2. Land-use change

Fig. 4 show the impact of land-use change expressed as either pavement of urban areas (increase of fraction imperviousness) or as unsealing and infiltration (decrease of fraction imperviousness). Again the impact on ponded volume outreaches the impact on discharges. The highest increase can be seen for RP=1 (events 1 and 5) with an increase of about 1,000% and 950% respectively. Here it's again important to note that this increase in percentage is based on a relatively low flooding volume for the baseline system of 1,114 m³ and 458m³ for event 1 and event 5 respectively.

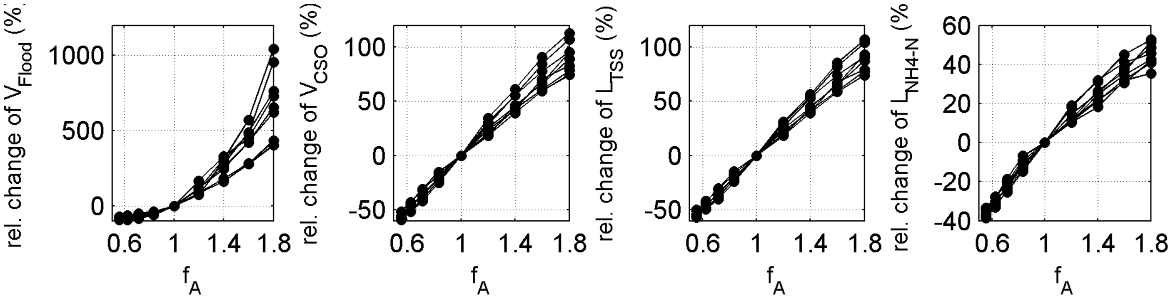

Fig. 4. Impact of pavement on (a) ponded volume (m3); (b) CSO discharge (m3); (c) TSS discharge (t); (d) NH4-N discharge (t)

3.3. Climate change effects compared to land-use change

Further it is possible to express impact of climate change and land-use change as a change in return periods of investigated events. Fig. 5 shows such an evaluation for the rainfall events 1 to 4 and for performance indicators V_{Flood} and V_{CSO}. This evaluation is based on an interpolation between return periods, CCF and f_A. For example, when assuming an rainfall increase by CCF=1.4 for rainfall event 3 (RP=3), this event has the same impact as an event with RP=8.

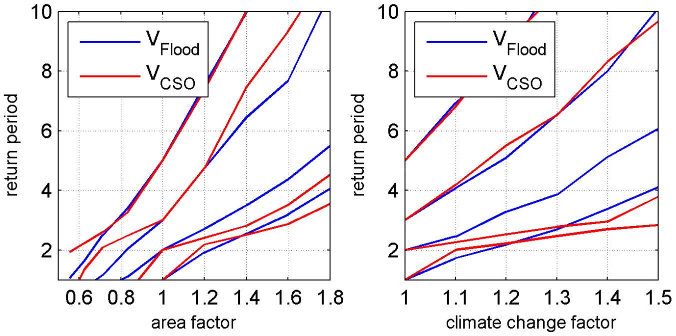

Fig. 5. Impact of CCF and expressed as change in return periods.

By comparing impact of climate change factors and impact of area factors it is possible to evaluate the sensitivity of the system response to changing conditions. As the system performance P can be expressed as a function of CCF and f_A (assuming constant rainfall input) it is possible to evaluate which impacts have similar effects. Fig. 6 shows such an evaluation for ponded volume and CSO discharge for all analyzed events. As can be seen an increase of rainfall intensities by CCF=1.5 has approximately the same effect as an increase of paved area by 80% (f_A=1.8). On the other hand side this increase of rainfall events could be compensated by a reduction of paved area by -40%

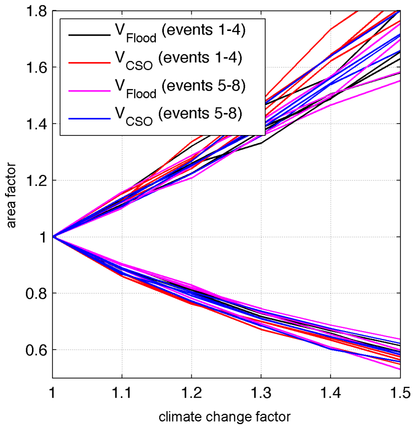

Fig. 6. Comparison of impact of climate change factors and impact of area factors

It is an interesting outcome that this comparison always is near-linear for different rainfall events and different performance indicators (despite the different behavior of different rainfall events shown in section 3.1).

4. Conclusion and outlook

This paper presents first results of a climate change and land-use change impact study for an Alpine case study. The impacts evaluated here are not realistic predictions but represent a sensitivity analysis to compare impact of higher rainfall intensities and increase/reduction of paved area. It can be seen that both impacts result in a similar figure when looking into flooding volume, combined sewer overflow discharge, total suspended solids discharge and ammonia nitrogen discharge. Hence it is important to look into both aspects when trying to predict future performance of combined sewer systems.

With increased runoff (either caused by climate change or pavement of urban areas) the impact on investigated performance indicators is near-linear. This means no tipping points in the system behavior can be identified. This is an important outcome when planning adaptation strategies as in such a case no sudden changes in system behavior have to be expected. Despite the fact that the results are derived for a specific case and are thus not generally transferable there is reason to believe that other sewer systems will not behave fundamentally different.

The next steps of this study will be realistic climate change and land-use projections for this case study. First results of the land-use projection and the model of the urban development are shown by Mikovits et al. (2013). Climate change projections will be based on recent regional climate model runs (Loibl, 2010) and empirical statistical downscaling procedures as described by Jasper-Tönnies et al. (2012). Based on these predictions, simulations of pluvial flooding and its associated risk of damages and combined sewer overflow discharges will help to develop effective adaption strategies with taking into account the temporal dynamics of a growing city and its water infrastructure.

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