# Assessing the hydrologic performance of an urban catchment that combines Stormwater Best Management Practices (BMPs) and Low Impact Development (LID)

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## ABSTRACT

Combining Best Management Practices (BMP) with Low Impact Development (LID) to manage storm water of urban catchments with separated sewer systems is a promising approach for sustainable stormwater management (SWM) in cities. Current research focuses on water quality issues, as well as lifetime, performance and optimization strategies to minimize impacts of urbanization on the watershed and meet different stakeholder demands. However, experimental data are rare that allow investigations of the hydrologic performance of sites with various BMPs and LID practices under site-specific conditions. In this study, the hydrologic and hydraulic response of a complex BMP-LID site was assesses by continuously monitoring precipitation, storm runoff discharge and river water levels over 18 months. The actual hydrologic performance was compared with design assumptions that were derived from the Rational Method by focussing on 4 criteria: reduction in runoff volume and in peak discharge, natural water balance and flood mitigation. Although the BMP-LID site exhibited a large variability with respect to these criteria, the overall estimates regarding water balance and annual volume reduction were fulfilled. Runoff volumes higher than design expectations and high discharge rates were attributed to heavy storms. Furthermore, the general influence of antecedent moisture conditions and snow melt during freezing periods were prominent. The observations under field conditions allow implications for optimization strategies regarding design assumptions, calculation and modeling but also possible retrofitting of the BMP-LID site.

## KEYWORDS

BMPs, hydrologic performance, LIDs, Rational Method, stormwater volume control, Sustainable Stormwater Management, urban drainage, urban modeling

# 1 INTRODUCTION

The use of concepts such as Best Management Practices (BMP) and Low Impact Development (LID) to control the quantity and quality of storm water runoff in terms of a sustainable storm water management (SWM) has evolved from the growing knowledge about the impacts of urbanization on the environment. The overall framework of SWM has expanded from focusing solely on flood control and drainage, towards taking into account impacts on the receiving streams (Muthukrishnan et al., 2006a), on the local water balance (Sieker et al., 2009) and on the groundwater (Goebel et al., 2004). Current legal requirements for surface and groundwater quality and ecology as defined e.g. by the European Water Framework Directive (EU WFD, 2000) or the U.S. Clean Water Act (in Copeland, 2010) pose new challenges to the SWM of urban catchments and require comprehensive approaches on a watershed scale (EC, 2012). In addition, SWM concepts emerge that take into account ecological but also economical and social aspects such as recreation and urban landscape (Stahre, 2008).

For many of these purposes, BMPs and LID show a great potential and advantage compared to conventional SWM. They can be efficient in reducing runoff volumes, discharge rates and pollutant loads but they can also be integrated in urban landscaping (green architecture). Given their small size, they might face less political and economical constraints (Urbonas, 2000) and can be used for retrofitting developed areas.

LID is a SWM design strategy that mimics natural processes such as infiltration, evapotranspiration, filtering, storage or detention by distributed micro-scale controls (e.g. green roofs, trees, pervious paving) that reduce runoff and pollutant loadings close to its source, including the preservation of open space and native vegetation (GC and WWE, 2009). The primary goal of structural BMPs such as infiltration trenches, vegetated swales, bioretention was traditionally seen in pollutant removal, but they can also be effective in reducing overflow runoff to the stream by enabling infiltration (GC and WWE, 2011).

Though there are still doubts by legal authorities in implementing BMPs and LID (Sieker et al., 2007, Stahre, 2008, TCF, 2007) and there are still many open questions by research regarding long-term risks and actual performance (Mikkelsen et al., 1997, Pitt et al. 1999, Goebel et al., 2004, Urbonas 2000), the approach of combining several structural BMPs and LID practices to control storm runoff quality ("treatment trains", Urbonas and Roesner 1993) and quantity seems promising (Villarreal and Bengtsson, 2004, Bastien et al., 2010). Several, though rare, studies, using paired watershed study designs, have shown that the impact of urbanization on the watershed can be minimized substantially, even to the predevelopment level, by LID practices (GC and WWE, 2009).

However, the complexity of BMPs and LID practices within an urban catchment and their effects on the watershed are hard to assess and model (Urbonas and Roesner, 1993). There is a need to fully understand and reasonably model the hydrologic and hydraulic response of complex BMP- and LID-sites under site-specific conditions in order to improve design and planning. For BMP controls, Urbonas (2000) points out that they are used without full understanding of their limitations and their effectiveness under field conditions that often do not resemble regulatory expectations or academic beliefs.

To assess uncertainties in design and site-specific variability, monitoring studies and performance assessment of real LID- and BMP sites is needed, as well as the clear definition of design criteria and goals. Some guidance is given on monitoring BMPs and LIDs on a site-level but so far, most of the existing studies focus on single measures on a practice-level (GC and WWE 2009).

With this study, the authors present a monitoring study that investigates the cumulative hydrologic performance of a combination of BMPs and LID practices in controlling volume and discharge rates of storm water runoff on a 10 year old site and under field conditions. By analyzing continuous measurements of rain, overflow discharge of storm runoff and stream gauge from 18 months of observation, we evaluated a BMP-LID site on an event-scale and compared it with design goals from the planning in 1996. We focused on 4 different aspects of:

- Reduction in runoff volume
- Potential restoration of a predevelopment, annual water balance
- Attenuation of peak discharges of overflow runoff to the receiving stream
- Flood mitigation

Controlling runoff volumes and discharge rates (“hydrologic performance”, GC and WWE, 2011) to mimic predevelopment conditions is regarded as a suitable approach to address hydromodification impacts on the receiving waters such as stream channel erosion, flow alteration, sedimentation, turbidity, temperature changes, habitat alterations (Booth et al., 1997, Sieker et al., 2009, GC and WWE, 2011). In addition, the control of storm water quality, though not monitored in this study, is closely linked with quantity control (e.g. Urbonas et al., 2011).

Re-establishing a water balance close to predevelopment conditions is another approach for minimizing the effects of surface sealing caused by urbanization (e.g. Sieker et al., 2009) because groundwater recharge is enabled, surface runoff is reduced and evapotranspiration is increased.

Reduction of flood risk by minimizing peak discharges of urban runoff and by delaying the peak discharge relative to the river flood wave is especially important for smaller rivers with smaller catchments in densely built-up areas.

The primary scope of this study is to test whether the actual hydrologic performance of the complex BMP-LID site is coherent with former design objectives. If the combination of structural BMPs and LIDs is successful in controlling volume and rate of stormwater runoff, it would confirm that there are reliable alternatives to “end-of-pipe” solutions for areas with small receiving streams and with site-conditions that are unfavorable for infiltration i.e. a low permeable subsurface and shallow groundwater, as is the case in the study area.

The comparison with design objectives allows some conclusions, whether the Rational Method that was used for designing the site in 1996 was appropriate in estimating reasonable goals for the site. Given the complexity of dispersed BMPs and LIDs, continuous simulation is time-consuming, and Urbonas et al. (2011) state that a complex method does not necessarily produce more accurate predictions because of the many assumptions on the parameters.

The investigation of the actual limitations of the studied BMP-LID site provides the basis for future optimization concerning design assumptions, calculation and modeling but also possible retrofitting of the site. The increasing complexity of LID- and BMP sites, the variability of site-conditions and the climatic changes demand a critical assessment of the weak points in predicting the hydrologic behavior of decentralized SWM systems.

## 2 METHODOLOGY

### 2.1 Study area

The studied urban catchment is part of a suburb called Vauban and drained by a separated sewer system. Situated in the city of Freiburg, federal state Baden-Württemberg, Germany, the area has been redeveloped as a residential area since 1996. The SWM of the site comprises a combination of structural BMPs and a variety of distributed decentralized LID practices. The normally-dry BMPs comprise 27 vegetated swales (detention volume: 1.8 watershed-mm) that facilitate on-site retention, infiltration and pollution control and form 2 cascaded lines within the catchment (Fig.1). Each swale is connected with the swale downstream by either overflow pipes or an overflow spillway. If the collected surface runoff exceeds the retention capacity of the swales, runoff is conveyed by the swale system to a single overflow outlet, where excess runoff discharges freely to a nearby small river. Each swale is built of a layer of 0.5 m topsoil and 0.2 m sand. Underneath each swale, percolation trenches (void ratios backfill material 0.35 to 0.95) account for additional underground storage (storage volume: 4.2 watershed-mm) and facilitate exfiltration to the aquifer. They are fed from the top by the percolation waters from the swales. LID practices on public and private land comprise permeable pavements, large trees, 5 green open spaces (1.5 ha), vegetated and pebble roofs, rain water use with barrels or cisterns and vegetated front and back yards as lawns or flower beds (Fig.1). Most of them are rather landscape practices. If storm runoff exceeds the retention capacity of the LID practices, the storm water is conveyed to the swale system via open gutters, inlets and pipes. LID practices that reduce the generation of runoff were necessary because the site-conditions for stormwater infiltration were marginal (clayey silts, silty clays as topsoil, shallow groundwater) and the stream was already showing degradation due to urban discharges from other sites. River discharge is approximately 4400 L/s for the 2 year-flood. Discharge of groundwater to the stream can be assumed as negligible for this river section. All excess storm runoff leaving the site as discharge is captured by the single overflow outlet to the stream (no bypass flows).

| | |
|---|---|
| average runoff coefficient (actual land use): | 0.45 |
| whole connected area (in ha): | 15.35 |
| **actual landuse + LIDs** | % |
| roofs, balconies - conventional | 13 |
| roofs, balconies - vegetated | 13 |
| roofs - pebble | 1 |
| streets, lanes - asphalt | 9 |
| streets, lanes, open spaces - permeable paving | 13 |
| open green spaces – grass + shrubs + trees | 8 |
| flower beds and gardens, yards - flowers | 9 |
| lawns, swales, tree pits – grass | 33 |
| multi-family residential, flat topology, | |

Figure 1. Aerial view (City of Freiburg, 2008) on the studied catchment with location of observation points and sketch of the central BMPs (swale-trench infiltration system) and percentages of land use and LID

The overall size of the site's structural BMP design was calculated in 1996 using the Rational Method. A 15 min 5-year design storm (20.2 mm) and 4 land use types (building, streets, green areas, private driveways) yielding a mean design runoff coefficient of 0.42 were used in 1996. Initial loss of 2.5 mm was assumed for the site and a design soil infiltration rate for the BMPs of $5*10^{-6}$ m/s, which is half of the rate defined in German technical guidelines (DWA, 2005).

## 2.2 Monitoring network

A precipitation gage and water level measurements to obtain discharge at the overflow outlet and the receiving stream have been operated since July 2010. The heatable tipping bucket precipitation gage was installed on a roof top (20 m above ground) and precipitation was recorded in 1 min intervals and 0.1 mm resolution. Data were cross-checked with data from a nearby station.

Discharge of storm runoff leaving the catchment was derived from the recorded water level in 1 min intervals with an absolute pressure transducer data logger (Diver-Baro, 1.5 m FS, 0.3% accuracy), compensated for atmospheric pressure and temperature. The probe was installed in the overflow pipe (open channel) of the drainage system that acts as outlet and connection to the receiving stream. The rating curve (water depth – flow rate) was calculated using a hydraulic 1D-simulation of the overflow pipe and the river section with the software *HEC-RAS*, taking into account possible backwater affects. Water levels less than 3 cm (5 L/s) were uncertain and were only considered as a qualitative information if discharge was activated or not. The water level in the receiving stream was measured at 5 min intervals with a capacitance water level logger (Odyssey) and later with a hydrostatic water level data logger.

Individual storm events were defined by rainfall amounts larger 0.2 mm and separated by a 4-hour inter event dry period. Snow will only be considered in this study in monthly and annual sums but not for single events. Rainfall intensity is given as maximum mean intensity $I_5$ (mm/h) for a 5 min duration interval.

## 2.3 Hydrologic measures

The hydrologic performance of the BMP-LID site as defined in this study was assessed with three measures: (1) runoff coefficient $RC$, (2) peak discharge of storm runoff and (3) time lag between peak discharge of the outlet and water level dynamics in the receiving stream.

Various inlets of the BMPs and the LID design of the study site did not allow measuring the inflow runoff compared to other BMP studies (GC and WWE, 2011). Hence, total precipitation was used as input and to calculate the runoff coefficients $RC$ for each event. The $RC$ reflects the hydrologic nature of the response and it can be used for comparison with other land uses and catchments. It was calculated as ratio of discharge volume $V_d$ and total precipitation volume $V_p$ on a storm-by-storm basis and named as $RC_{event}$. To account for antecedent soil moisture, a second event runoff coefficient $RC_{ant}$ was calculated by adding the retained storm volume of all prior events with maximum dry-periods of 24 h:

$$RCant = \frac{V_d}{V_p + \sum_i^n \left(V_{pi} + V_{pi+1} + \dots + V_{pn}\right) - \sum_i^n \left(V_{di} + V_{di+1} + \dots + V_{dn}\right)} \quad (1)$$

The maximum design threshold from 1996 for intense or long-enduring storm events had been calculated as $RC_{event}$ of 0.32 by applying the Rational Method to a variety of design storms. The design goal for cumulative annual storm reduction was an $RC$ of 0.13, which was based on mean annual precipitation and mean initial losses.

$RC_{event}$ indirectly expresses the fraction of storm volume captured by the BMP-LID site, i.e. the fraction of storm volume retained by infiltration, evapotranspiration and re-use, as well as interception, wetting loss and depression loss. The design objective was a maximum storm volume capture (*SC*) for each storm event, which can also be expressed as:

$$SC = 1 - RC_{event} \tag{2}$$

The assumption of 37% infiltration, 50% evapotranspiration and 13% runoff discharge was considered as a water balance corresponding to a natural watershed in this region. Hence, a cumulative annual *RC* < 0.13 would indicate, that the potential to re-establish a predevelopment water balance for this region could be achieved within the observation period.

The planning in 1996 did not yet consider predevelopment discharges as threshold for maximum peak discharges. However, according to current state of the practice, predevelopment discharge was calculated as 230 L/s using an RC of 0.1 and a 30 min 5-year design storm (26.5 mm). During planning in 1996, it was assumed that heavy storm events would disable the retention function of the BMP-LID site so that the swale system acts solely as conveyance system. For this case, a maximum discharge rate of 940 L/s had been calculated for a 15 min 1-year design storm (12.5mm), which served as a design assumption value in this study. To qualitatively assess the potential of hydraulic stress for river organisms, a term used e.g. by Sieker et al. (2007) to describe the disturbance of benthic river organisms by drainage discharges, the ratio of peak discharge compared to the river discharge was used as indicator, though no threshold value can be given here.

The aspect of flood mitigation was investigated by calculating the lag times between peak discharge at the outlet and the flood wave in the receiving stream for the 4 highest river flood events.

## 3 RESULTS

A total of 194 storms were measured over 18 months of record with 46 events causing stormwater discharge to the river (Fig.2), which corresponds to an average discharge frequency of 3 times per month.

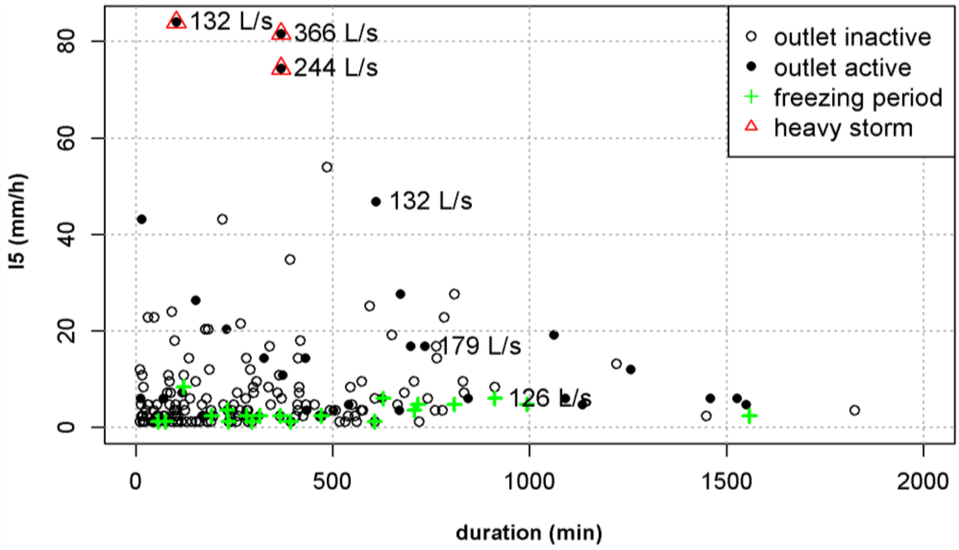

Figure 2. Duration and maximum intensity $I_5$ (5 min interval) of all observed storms. Filled dots qualitatively indicate that stormwater discharge to the stream took place with peak discharge rates printed for the 6 highest discharge events.

The activation of the outlet to the stream was not directly linked to the storm characteristics (Fig.2). By comparing maximum intensities for several duration intervals with rainfall intensity-duration-frequency curves from a permanent station in the city of Freiburg, it was found that 3 of the observed storms show peak precipitation rates comparable to storms with recurrence intervals of 0.5 to 2 years. They are classified as heavy storms in this study, maximum intensities of 30 to 60 mm/h will be referred to as moderate storm and below 30 mm/h as weak storm.

Intense but rather short storms occurred exclusively in the summer months June to August, whereas less intense storms of longer duration were observed throughout the year. The monthly rainfall of the observation period differed from the long-term climatic means for Freiburg (Fig.3).

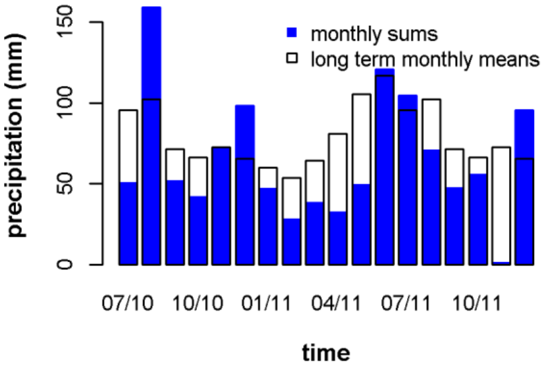

Figure 3. Monthly rainfall for the observation period compared to long-term climatic means for the city of Freiburg (1961-90, data: LUBW), annual sum (2011): 691 mm, long-term annual mean Freiburg: 933 mm

During winter (25.11.2010 - 24.2.2011), weekly periods of frost (up to -10 °C) and snow accumulation alternated with periods of temperatures above 0 °C accompanied by sustained rain events that initiated snow melt and caused floods. It is highly likely that due to freezing or thawing and re-freezing of the uppermost soil layer, infiltration processes were inhibited. During this period, 14 rain events produced discharge, often accompanied by snow melt (crosses in Fig.2). This period is referred to as “freezing period” in this study because it is a special case and it might be of importance for urban drainage planning and flood mitigation.

## 3.1 Reduction in runoff volume

To assess the volumetric effectiveness of the BMP-LID site, both runoff coefficients $RC_{event}$ and $RC_{ant}$ are displayed relative to the 0.13 and the 0.32 line (Fig.4) for events with peak discharges greater than 5 L/s. $RC_{ant}$ accounts for a possible pre-saturation by preceding rains. If both RCs plot in the same place for one event, the influence of antecedent moisture can be regarded as low, indicating that the runoff response was affected solely by the characteristic of the storm. The 0.32 line indicates whether the storm capture for each event was within the maximum range of design criteria i.e. below the dashed line. *RCs* below the 0.13 line indicate optimal volume reduction according to design goals.

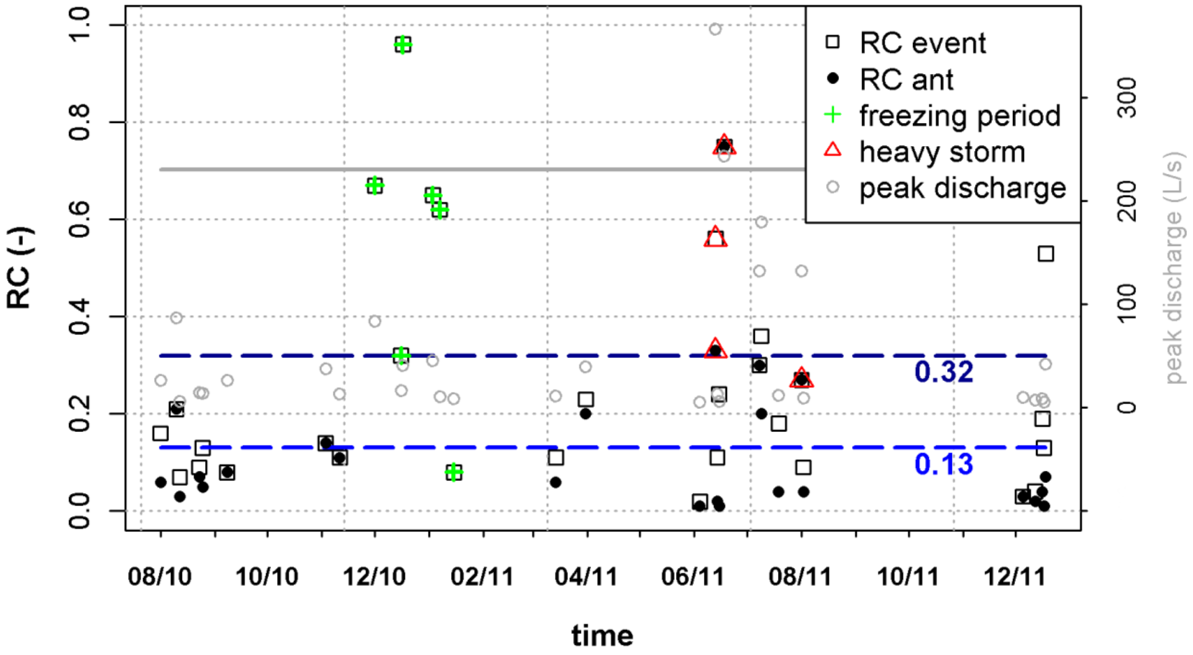

Figure 4. Runoff coefficients $RC_{event}$ and $RC_{ant}$ (for discharges > 5 L/s) with respect to the average annual design criteria (0.13) and maximum event design criteria (0.32), and peak discharges with respect to the theoretical predevelopment line of 230 L/s. Freezing periods with *RC*s > 1 due to snow melt are not displayed.

The highest $RCs_{event}$ are attributed to freezing periods, where often snow melt added to the storm runoff yielding $RCs_{event}$ values up to 4 that are not displayed in Fig.4. Furthermore, high $RCs_{event}$ were observed for 2 heavy storms during summer, which lasted 360 min and had maximum intensities comparable to 0.5 to 1-year storms. Comparing $RC_{event}$ and $RC_{ant}$ for the non-freezing periods shows that in most cases, antecedent moisture was the reason that runoff reduction was not within the design goals. A comparison with the 0.32 design criterion shows that out of 25 events that produced storm discharge (> 5 L/s) 24 prove a performance (96%) within the design goals provided that antecedent conditions are taken into account. If the saturation by preceding rain is not considered, only 21 events (84%) prove a good performance. Taking cumulative sums yielded an annual *RC* of 0.13 for the year 2011, which is equal to the mean annual design goal and corresponds to an annual storm volume capture *SC* of 0.87.

## 3.2 Attenuation of peak discharges

The highest peak discharges were observed in June to August 2011 (Fig.4). They were related to storms that also exhibited high $RCs_{event}$ (Fig.4). Two out of 25 peak discharges (8%) exceeded the theoretical predevelopment level and are attributed to heavy storms of about 360 min duration. A heavy storm of comparable size and intensity but only 100 min duration produced discharges within the predevelopment level. All of the observed peak discharges stayed well below the maximum design value of 940 L/s. The highest hydraulic impact on the river ecology is caused by discharge rates that are high compared to the discharge of the river itself. Two groups of impact ratios were observable by calculating the ratios of peak discharge and river discharge for the moment of the 6 highest peak discharges: Comparatively low ratios of 0.03 to 0.05 occurred during the freezing period, under wet antecedent conditions and for one heavy but rather short storm under dry antecedent conditions. Higher hydraulic impact ratios of 0.13 and 0.17 were observed for a moderate storm and for a heavy storm, both of which began under dry antecedent conditions.

### 3.3 Flood mitigation

The attenuation of peak discharges also contributes to flood mitigation. However, the time lag between river flood wave and discharge from the drainage is particularly important and showed a high variability for the 4 highest flood waves that occurred in the river during the observation period (Fig.5). In 2 cases, the peak discharge entered the river about 29 to 105 min after the flood crest (5.8.2011, 22.6.2011), which helped mitigating the flood wave. In contrast, for 2 other cases, the discharge peak arrived only a short time after the flood crest with only 5 to 10 min delay, thus it is highly likely that it amplified the flood wave (17.6.2011, 13.7.2011).

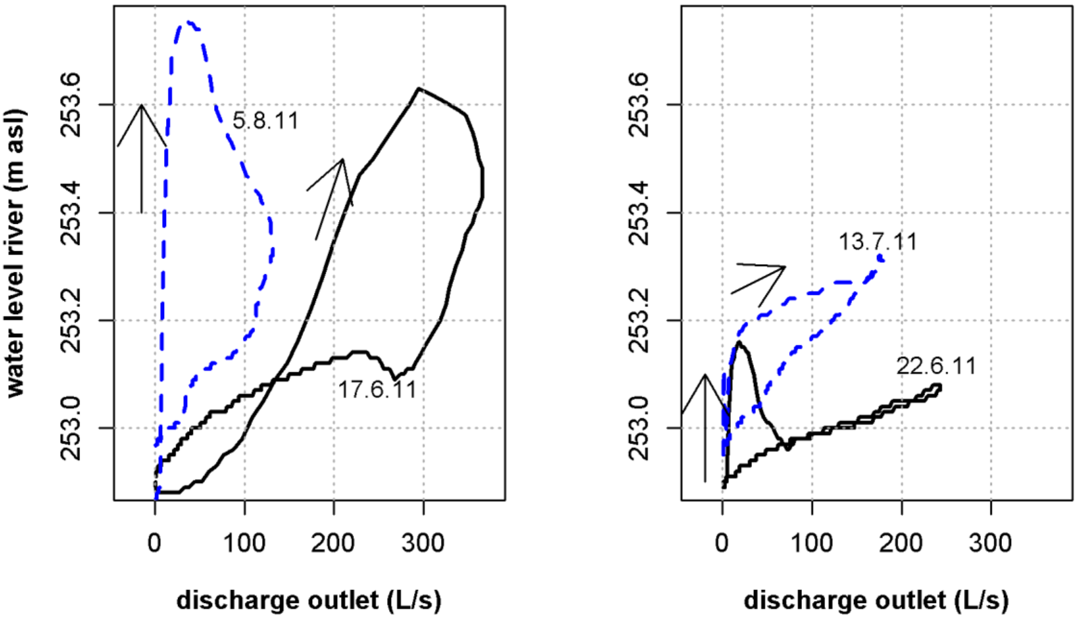

Figure 5. Temporal behavior of discharge at the outlet and river water level during the 4 largest flood waves. Arrows indicate the rising limb.

## 4 DISCUSSION

### 4.1 Reduction in runoff volume

Analysis of the annual runoff coefficient showed that the hydrologic performance concerning volume reduction of the BMP-LID site during 12 out of 18 months of observation met the design assumptions looking on an annual scale. A storm-based analysis reveals that exceptional high amounts of discharge, largely exceeding the design goals occurred during freezing periods with additional inflow from snow melt. Since those conditions were not covered by design calculations, it already indicates a weak point in the planning but also a limitation of the BMP-LID concept itself. During non-freezing periods, weak to moderate storms rarely undercut the aimed volume reduction and only when antecedent moisture from preceding rain was present. This reflects that the runoff response of the BMP-LID site is storage dependant. This observation supports the theoretical statement that the amount of stormwater expected to discharge especially from a LID site is strongly influenced by the quantity of remaining storage volume (GC and WWE, 2009). The critical effect of antecedent moisture on the volume reduction has also been observed in other studies e.g. for the performance of green roofs (Stovin, 2010). The largest observed storm size was 26 mm, so that no conclusions for storms beyond this size are possible. Concerning heavy storms, the observation of sufficient volume reduction even for a heavy, though short (100 min) summer storm under dry antecedent moisture conditions indicates that the BMP-LID site is able to mitigate heavier storms provided that all rapidly accessible storages such as vegetated roofs, permeable paving and retention volume by ditches and green areas are available. In contrast, for some heavy storms of longer duration (360 min), BMPs and LID practices failed to perform as expected from design calculations, which is most likely due to the combination between available storage volume and the characteristic of the storm. To draw general conclusions on the relationship between storm characteristics and response of BMP-LID sites, a longer time series would be necessary. Conceptually, the volume reduction of BMPs that facilitate infiltration and especially of LIDs depends not only on the remaining storage volume that is governed by antecedent moisture but also on how quick it is accessible for storms of strong intensities. Furthermore, for consecutive storms, the available storage volume will depend on the recovery of the storage over time (GC and WWE, 2009).

The observation of runoff reduction lower than expected caused either by heavy storms from June to August or by freezing periods in the winter indicates a seasonal effect. The volume reduction performance of the BMP-LID site seems most vulnerable during summer and winter. Comparing event runoff coefficients with the annual runoff coefficient showed the importance of the time-scale of data aggregation when evaluating the runoff reduction of BMP-LID sites. In the present study, the seasonal variability would have been masked when averaged annually.

The observation of volume reduction showed that most of the weak to moderate storms that occur more frequently than twice a year are retained completely or at least by 68% of its volume by the BMP-LID site. Amongst others, Urbonas (2000) points out the importance of capturing especially the small, frequently occurring storms to enhance water quality in the effluent to the watershed, as well as the first flush events of larger storms because they carry the highest pollutant loads. Given the retention mechanism of the BMP-LID site, which first captures storm runoff until all storages are filled and later on allows discharge, it can be assumed that the first portion of storm runoff volume is usually retained by the site even for heavy storms.

### 4.2 Water Balance

Taking the observed annual runoff coefficient of 0.13 for the year 2011 as a rough indicator for the water balance of the urban catchment, we can further conclude that on an annual scale, about 87% of all storm water was captured by the BMP-LID system. Thus, the potential to re-establish a near-natural water balance existed for the redeveloped site, neglecting the precise proportions of evapotranspiration, infiltration and use. Given the shortness of the current data set, a long-term water balance (i.e.> 5 a, GC and WWE, 2009) cannot be assessed but would be a more robust performance descriptor.

### 4.3 Attenuation of peak discharges

Within 18 months of observation the combination of BMPs and LID practices was effective in controlling peak discharge rates below the theoretical predevelopment level, except for 2 heavy storms in the summer. Although the definition of a predevelopment level is based on theoretical assumptions, it allows a rough estimate on the behaviour of a comparable site with natural land use.

Analyzing the highest peak discharges revealed that they were usually produced by those events with the highest event runoff coefficients under non-freezing conditions. While discharge volumes caused by storm runoff and snow melt in the winter can be extremely elevated, the rate of discharge stayed below the theoretical predevelopment level. In contrast to the seasonality of the volume reduction performance, the ability of the BMP-LID site to reduce peak discharges seems to be critical solely in the summer months.

All observed discharges stayed below the maximum design peak discharge of 940 L/s. Even for those storms with characteristics similar to the according design storm, the discharges stayed well below. This indicates that the design assumption on the BMP-LID site in losing its retention capacity for storms with high intensities is in disagreement with the field observations of this study.

The highest hydraulic stress for river ecology, as derived from hydraulic impact ratios, was created by moderate to heavy storms after drier periods when flow in the river was low. Since this situation is characteristic for the summer months, this points to the unfavorable combination of summer low flows in the river and highest peak discharges caused by heavy storms during summer. In order to improve the mitigation effect of the BMP-LID site for peak discharges, additional short term storage volume would be necessary e.g. by additional retention of green and pebble roofs, ponds etc. or regulating the outlet discharge rates by a curbed outlet.

### 4.4 Flood mitigation

Although river floods are already mitigated to some extent by reducing peak discharges, the concept of delaying runoff discharge with respect to the flood crest of the stream was an aim of the design. Unfortunately, no design threshold values had been calculated, which is probably due to the complexity of estimating concentration times and flow routing for sites with combinations of various types of BMPs and LID practices. However, the current study was supposed to give some first ideas on the potential of the BMP-LID site in mitigating floods. Given the high variability of observed lag times, no general conclusion can be drawn for the site but the general potential could be proven with lag times ranging from 5 min to 105 min. The variability of lag times reflects the variability of the hydrologic response of the site as already described earlier. Given that the implemented BMPs and LID practices remove storm water by infiltration and evapotranspiration, the hydrological response is a complex interplay between available storage volume, storage recovery, storage accessibility and storm characteristic, making it even harder to assess a specific design for flood mitigation.

It shall be noted, that there seems to be a discrepancy between the objectives of river ecology and flood mitigation. If high peak discharges happen during low stream discharges, the hydraulic impact on sensitive river organisms increases. Especially cases where the outlet discharge approaches or exceeds the theoretical predevelopment level and stream discharge is low (Fig.5 right) are sensitive to hydraulic stress on river ecology or hydromodification.

## 5 CONCLUSIONS

The conclusions derived from monitoring precipitation, storm runoff discharge and stream water levels for 18 months represent the aggregate hydrological response of the BMPs and LID practices implemented on the site.

The annual volume reduction and the reduction of peak discharges to a predevelopment level were mostly within the design objectives, which indicates that even under site-conditions that are unfavorable for infiltration, the combination of structural BMPs (swale-trench infiltration) combined with LID practices can be effective in managing storm water quantity. Given the short observation time, we are not able to actually quantify the hydrologic performance in order to give general results or to judge the overall hydrologic effectiveness of the site. However, the comparison with design goals on a storm-by-storm basis indicated some limitations of the BMP-LID site, as well as seasonal trends that are likely to occur regularly such as: Storm events with higher discharge volumes than expected by the design goals can be attributed to heavy, less frequent storms during the summer months and snow melt and freezing periods during the winter season. Peak discharges above the assumed predevelopment level were caused by heavy storms during the summer months.

The annual storage capture volume as concluded from 12 months showed that with the BMP-LID design of the site the potential is given to re-establish a predevelopment water balance, though neglecting the proportions of evaporation and infiltration.

The observations of the volume reduction of the BMP-LID site and its fundamental hydrologic behavior of mitigating most of the small and frequent storms as well as conceptually retaining the first flush of larger storms indicate that also benefits in storm water quality can be expected. Muthukrishnan et al. (2006a) and others describe that pollutant removal capabilities of BMPs looking at effluent concentrations and loads is also affected by the hydrologic response of the site to different rain events and under different environmental conditions.

The observation of highest peak discharges occurring in the summer season during low flow conditions in the river infers that the potential of hydraulic stress and streambed erosion increases during the summer seasons. This study indicates that looking exclusively at peak discharges from urban runoff is not sufficient in mitigating adverse effects on the river but also the stream discharge itself is important.

The flood mitigating effect of the BMP-LID site showed a large variability. However, the fact that for some cases a substantial delay between peak discharge and river flood wave was observed points out the potential of the BMP-LID site in mitigating floods. Further investigation is necessary using high-resolution, continuous monitoring data.

To improve the site, especially for the mitigation of heavy storms, additional BMPs and LID practices that provide retention and storage independent of infiltration rates could be useful. For example additional green roofs that are especially effective in controlling intense, short-duration summer storms with cumulative summer runoff reductions of up to 80 to 90% (Muthukrishnan et al., 2006b).

The comparison of actual field observations with design goals derived with the Rational Method showed that the method was sufficient in predicting reasonable estimates on the annual and storm-based volume reduction of the complex set of BMPs and LID practices. However, the specific design approach over-estimated the volume reduction for most of the observed heavy storms even though design storms of greater size and larger intensities were used than the observed ones. The critical influence of antecedent moisture and freezing periods on the reduction of runoff volume and peak discharge were not considered in the former design calculations but have been proven to be of essential importance for the BMP-LID site. The planning assumption that attenuation of peak discharges by BMPs and LID practices is completely disabled for heavy, less frequent storms could not be supported with the observations. For future design of BMP-LID sites using the Rational Method, we suggest using a broad spectrum of design storms, especially of sizes that exceed the expected storage volume of the planned site. Combining them with dry but also saturated antecedent moisture conditions for calculation purposes would be useful. The temporal inhibition of infiltration during freezing periods and the additional runoff caused by snow melt should also be taken into account. If continuous simulation with long-term precipitation data sets is used to design or optimize BMP-LID sites, it is crucial that antecedent moisture conditions, soil conditions representing freezing periods and a snow routine are implemented. Especially the strong influence of antecedent moisture on the available storage of the BMP-LID system and reliable recovery rates for the different types of storages need to be reproduced by models. Borst et al. (2006) point out that a major source of error in hydrologic predictions is caused by the inability to account for antecedent soil moisture conditions and its impact on runoff formation processes.

This study is an example of how continuous data sets can be used for evaluating the actual hydrologic performance of a complex BMP-LID site with a simple mass-balance approach, using simple measurement techniques. The differences between design goals predicted with the Rational Method and actual field observations underline that monitoring under field conditions, even for shorter time periods, is the only possibility of reliably assessing the hydrologic impacts of a BMP-LID site after its implementation. Although a monitoring period of 18 months is not sufficient in capturing the large inter-storm variability that is related with LID sites in general, the information obtained can be used for optimizing a site, especially concerning river ecology and flood mitigation.

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