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Efficiency of stormwater control measures for combined sewer retrofitting under varying rain conditions: Quantifying the Three Points Approach (3PA)

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Efficiency of stormwater control measures for combined sewer retrofitting under varying rain conditions: Quantifying the Three Points Approach (3PA)

We present a method to assess and communicate the efficiency of stormwater control measures for retrofitting existing urban areas. The tool extends the Three Points Approach to quantitatively distinguish three rainfall domains: (A) rainwater resource utilisation, (B) urban stormwater drainage pipe design, and (C) pluvial flood mitigation. Methods for calculating efficiencies are defined recognizing that rainfall is both a valuable resource and a potential problem. Efficiencies are quantified in relation to rainfall volume, supplied potable water volume and volume of wastewater treated. A case study from Denmark is used to illustrate how the efficiency varies between the rainfall domains. The method provides a means for communicating some important quantitative aspects of stormwater control measures among engineers, planners and decision makers working with management of water resources, stormwater drainage and flood risks.

Keywords: stormwater control measures; stormwater management; three points approach

1 Introduction

Management of urban stormwater, i.e. rainwater that runs off paved urban areas, is complex because of conflicting needs and objectives. Traditional stormwater management technology in the form of sewers is installed with the aim of draining stormwater efficiently to protect human health and human assets, but this practice often disturbs the natural water cycle and has a multitude of other detrimental environmental impacts (Schuster et al., 2005). Alternative stormwater management has gained increased attention in recent years due to different drivers such as aging infrastructure, a wish for more cyclical rather than linear systems (Chocat et al., 2007), and increases in size and occurrence of extreme rainfall due to anthropogenic climatic changes (Arnbjerg-Nielsen et al., 2013). A suite of newer structural and non-structural practices for stormwater management has emerged, reflecting the different perspectives involved and the needs for driving the stormwater profession in new directions. These are in the following called stormwater control measures (SCMs) and represent technologies such as stormwater best management practices (BMPs), green infrastructure (GI), low impact development (LID), sustainable urban drainage systems/sustainable drainage systems (SUDS/SuDs), and water sensitive urban design (WSUD) (Fletcher et al., 2015). We use SCMs in this article to refer to any combinations of practices, structures, or implemented technologies that seek to reduce the negative environmental impacts of sewer based stormwater systems. This is in line with the definition given by the Committee on Reducing Stormwater Discharge Contributions to Pollution (2009).

SCMs have a multitude of expected impacts and a range of indicators can be used to quantify these (Lerer et al., 2015). In the case of SCMs for stormwater harvesting there is often a conflict between the aim to reduce the impact on the natural water cycle and the aim to substitute drinking water. A related challenge exists in balancing the aim to manage large quantities over time, i.e. from an annual water balance perspective, and the aim to manage extreme rainfall, i.e. from a single event's perspective. Therefore, there is a need to better distinguish between the different functions SCMs may have when quantifying and reporting their efficiency, as the following examples will show.

Efficiency of an SCM expressed as a fraction of the total rainwater volume over extended periods of time, e.g. a year, can be misleading if used in a flooding context. For example, stating that an SCM controlling 60% or even 99% of the annual rainwater volume will reduce the risk of urban flooding (see e.g. Armson et al., 2013 for an example) may be misleading as the remaining 1% of the rainwater volume is composed of the extreme events with heavy peaks that exceed the design criteria for the SCM in question and cause floods. Stovin et al. (2013) used a lumped sewer model to show that the annual number of Combined Sewer Overflows (CSOs) can be reduced using "*aggressive implementation of SuDS*". The analysis considered catchments with very frequent CSOs (29-59 per year) and the rainfall events analysed had return periods of only two and four years. More extreme rainfall events are discussed in the study but no clear conclusions are provided. Locatelli et al. (2014) and Yang et al. (2015) both modelled and experimented with green roofs. Locatelli et al. (2014) validated a model for three different green roofs and subsequently evaluated their performance with respect to retaining water for a range of observed rainfall events. Yang et al. (2015) experimented with a wide range of precipitation input to a similar model to explore the performance under extreme conditions. Both studies showed a clearly decreasing performance as events become larger.

The examples above show two important aspects in the evaluation of SCMs: 1) Simulations with long time series of rainfall are necessary to determine how large a proportion of the maximum efficiency of SCMs can actually be utilised in a more close-to-real setting, and 2) it is necessary to calculate and present the efficiency of an SCM for both the annual volume and for individual extreme events separately because controlling of large volumes on an annual basis is not the same as provision of flood protection.

To provide consistent reporting and avoid confusing communication about the efficiency of SCMs, we suggest a method for reporting the efficiency of different approaches based on 'rainfall domains'. Our method extends the Three Points Approach (3PA) presented by Fratini et al. (2012), which defined three distinct decision domains, each governed by different professionals, affected by different stakeholders and subjected to different values. We redefine the three domains from a hydrologic perspective in terms of rainfall return periods relevant within the urban water cycle. This allows calculating quantitative efficiencies for a given SCM in each domain with respect to each flow, resulting in a matrix of metrics that together characterise the performance of the given SCM comprehensively and clearly. Our proposed method aims to facilitate better communication between different stakeholders about the efficiency of different stormwater management strategies by answering questions like: "*under what circumstances may rainwater harvesting systems and other stormwater control measures be expected to contribute efficiently to (A) rainwater resource utilisation, (B) urban storm drainage pipe capacity and (C) pluvial flood mitigation?*".

The method is applied to three theoretical SCM strategies for the City of Copenhagen, Denmark

2 Methods and data

All data analysis in this study is based on the assumption that a water balance can be made at the municipal level. In our study we focused on the rainfall above a defined municipal area and the engineered flows (stormwater runoff, supply of potable water and wastewater flow directed to the wastewater treatment plant) as these together pose the greatest cost to society (Kenway et al., 2011).

2.1 Defining the domains of the 3PA

In the original definition of The Three Points Approach (3PA) Fratini et al. (2012) delineated three distinct domains in which decisions related to stormwater management are made. They illustrated how the domains relate to distinct types of rainfall events that occur with different magnitude and return period, cf. Figure 1. Adopting an urban drainage engineer viewpoint, they labelled these typical rain events decision points from 1 to 3. *Point 1* refers to the most important point for the urban drainage engineer, the "what is my responsibility"-point, *Point 2* refers to the second most important point, the "what happens when the system capacity is exceeded"-point, and *Point 3* refers to the least important point, the "how could we do something alternative with the rainwater"-point. However, in order of increasing magnitude of rain events, Fratini et al.'s domains come in the sequence 3, 1, 2 and for quantitative evaluations, this numbering is less intuitive. Hence, we renamed the Points A, B and C, where the point corresponding to the smallest and most frequent events is named A and the point corresponding to the largest and rarest events is named C (Figure 1). This modification to the 3PA is relevant since SCMs perform differently for varying magnitudes of rain events. Furthermore, we redefine the axes to reflect rainfall magnitude (vertical axis) and rainfall return period (horizontal axis), allowing a quantification of the three points based on historical rainfall time series.

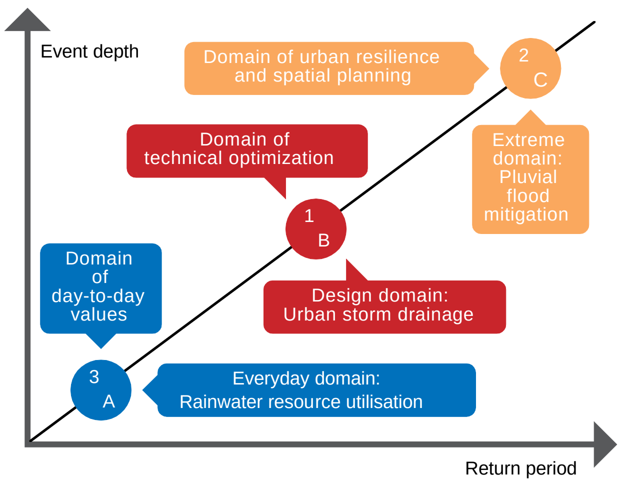

Figure 1. Conceptual definition of the 3PA domains. Fratini et al. (2012) defined the 3PA in domains 3, 1, 2 and we modified the labelling to A, B, and C in the order of increasing return periods.

Given these modifications we define the three rainfall domains in relation to the 3PA points as:

Point A: Rainwater resource utilisation or the everyday domain. With respect to rainfall this domain represents everything from dry weather to rainfall events that utilise the capacity of the urban drainage systems without causing any direct wet weather discharges to the environment. It acts as the design domain for a majority of decentralized SCMs such as green roofs and soakaways.

Point B: Urban storm drainage pipe design domain. The rainfall in this domain is described as events that traditional urban stormwater infrastructures are designed to manage. The domain covers from rainfall events that cause controlled overflows to surrounding water bodies and up until, but not including, rare rainfall events that are not considered feasible to convey using traditional sewer systems. In other words, this domain is capped at the point where floods from an engineering point of view are considered to be acceptable. It is the most well defined and regulated of the three domains. Performance requirements to sewers vary internationally, but everywhere in the world people have expectations to how sewers are designed and operated, and in many places, this will be regulated in detail by central guidelines and standards.

Point C: Pluvial flood mitigation, or the extreme domain. The rainfall in this domain includes the rare events that cause floods in the urban environment, where the sewer system no longer is sufficient to control the rainwater and where overland flows are substantial or even dominating the drainage of the affected area.

2.2 Quantifying the domains of the 3PA

To assign a characteristic rain event to each domain of the 3PA we analysed historical rainfall records considering different rain event durations (Jørgensen et al., 1998; Madsen et al., 2009). For each rain series we identified events according to the recommendations of Madsen et al. (2009) with a dry weather period between individual events of the same length as the event duration definition. The obtained events were ranked according to their maximum mean intensity over the event duration definition, and the return periods for the events were calculated using the Median plotting position (Rosbjerg, 1988):

$$T_m = (T_{obs} + 0.4) / (m - 0.3) \quad (1)$$

where T_m is the return period of an event with rank m and T_{obs} is the total length of the rain series. Event durations of 3, 12 and 24 hours were included in the analysis.

We chose a characteristic return period for each domain based on prevailing design standards in Denmark. The Danish design criteria for rainwater harvesting and usage were used to define Point A as T=0.2 years (Teknologisk Institut, 2002). The recommendation of the The Water Pollution Committee of The Society of Danish Engineers to design of combined sewers for a return period of T=10 years, which was adopted by most municipalities in Denmark, was used to define Point B (Water Pollution Committee of the Society of Danish Engineers, 2005). Point C principally includes all events with T>10 years, but in order to constrain the domain and quantify the point explicitly we chose a return period of 100 years, which is a commonly used design criterion.

Using these quantitative definitions of the three points, we assigned each rainfall event to its appropriate domain, summed up the rainfall volume in each domain and found the characteristic rainfall depths for each domain based on the historic rainfall records.

2.3 *Defining efficiencies of SCMs*

We use the term efficiency to refer to a given SCM's capacity for managing and hence altering flows in the urban water cycle. We define quantitative efficiencies (*E*) as metrics related to three major urban water flows (Figure 2): Rainfall, water supply and flow to the wastewater treatment plant (assuming the SCM is implemented in an area served by a combined sewer system).

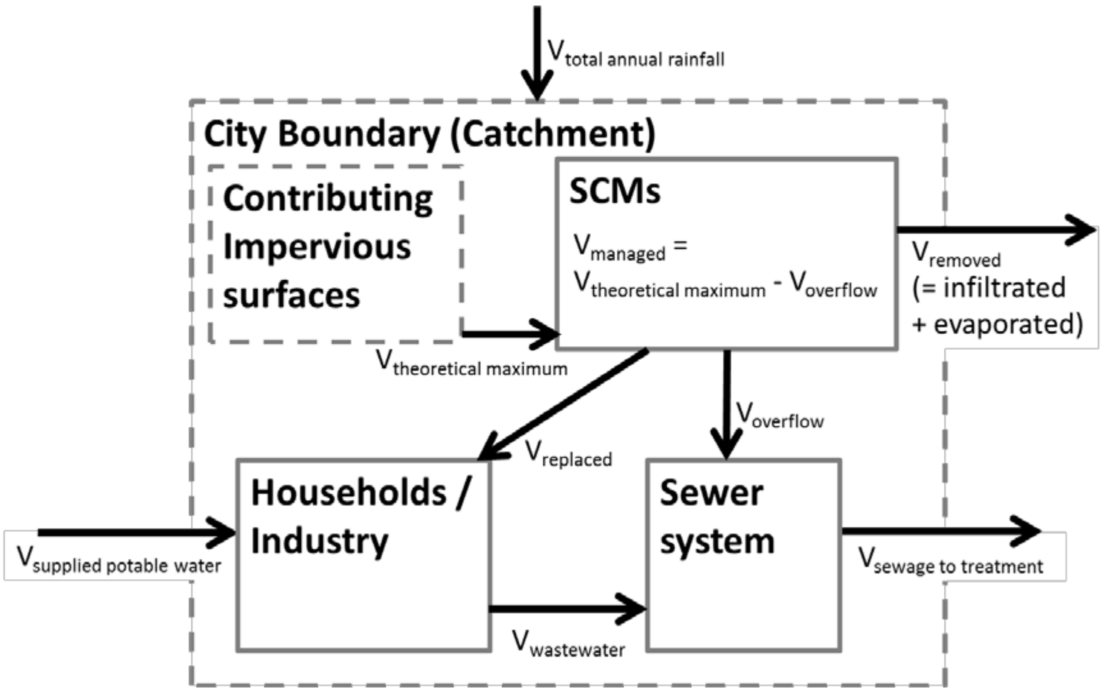

Figure 2. Major urban water flows relevant for SCM efficiency measures.

The efficiency related to volumetric Rainfall (E_r) expresses how well an SCM is able to exploit rainwater as a resource and is defined as:

$$E_r = V_{managed} / V_{total\ annual\ rainfall} \quad (2)$$

$V_{total\ annual\ rainfall}$ is the direct input flow to the city wide water balance and E_r thus depends directly on the spatial extent of the considered area. E_{rmax} is the spatially independent efficiency metric expressing the ratio between managed volume ($V_{managed}$) and the volume of rainfall received by the proposed SCM ($V_{theoretical\ maximum}$):

$$E_{rmax} = V_{managed} / V_{theoretical\ maximum} \tag{3}$$

The efficiency in reducing potable water demand (E_{pw}) is a measure of how much an SCM is able to decrease the potable water demand in the area of interest:

$$E_{pw} = V_{replaced} / V_{supplied\ potable\ water} \tag{4}$$

Finally, the efficiency in reducing the total wastewater production (E_{ww}) describes the degree to which an SCM is able to alleviate the load on the treatment plant:

$$E_{ww} = V_{removed} / V_{sewage\ to\ treatment} \tag{5}$$

Together these four metrics of efficiency are used to quantify the potential impact of SCMs on the major water flows in a city.

2.4 Conditioning the SCM efficiencies on the 3PA domains

The efficiency metrics defined above relate the individual volumes to key aggregated annual water flows. In the following we outline how they were further conditioned on rainfall domains using the 3PA. Hereby, the 3PA can be used to describe how well a system designed for one rainfall domain functions when exposed to the defining rain events of the other domains.

To calculate how much volume a structure designed for Point *i* manages when exposed to an event of Point *j* we extend Eq. 2 to 5 as follows, illustrated with E_r:

$$E_r^{j|i} = f_j\, g_{i,j}\, E_r \tag{6}$$

where f_j is the fraction of the total annual rainfall volume that falls within Point *j*. $g_{i,j}$ is the theoretical fraction of the rainfall that the SCM designed for Point *i* can manage when exposed to a Point *j* event. The sum of f_j's over all three points will always be 1.

$g_{i,j}$ will be 1 for the design point and for any point below (with lower return periods) and < 1 for any point above (with larger return periods); how much lower is determined using historical rainfall records.

The $g_{i,j}$ is an engineering abstraction that reflects how an SCM will act under ideal situations. In practice, the amount of rainwater an SCM can handle will depend on the specific rain event depth but also on the volume of water already stored in the SCM at the start of the rain event. Thus the $g_{i,j}$ calculated for each domain is a theoretical maximum value that can only be achieved by over-sizing of the SCM (Water Pollution Committee of the Society of Danish Engineers, 2005). Furthermore, the SCM capacity expressed by $g_{i,j}$ will be reduced if the magnitude and return period of considered events increase as the absolute amount of rainwater an SCM can handle is fixed.

2.5 The case study

The methodology outlined above was tested on the municipality of Copenhagen considering three types of SCMs: two strategies for stormwater infiltration (cases 1 and 2) and one strategy for rainwater harvesting (case 3).

2.5.1 Copenhagen municipality

Copenhagen is almost fully urbanised, with major suburbs being part of surrounding municipalities (see Table 1). The municipality has widespread combined sewer systems resulting in a very large fraction of stormwater in the inflow to the wastewater treatment plants under wet weather conditions (approximately 45% on an annual basis).

Table 1. Main attributes of the municipality of Copenhagen and its water balance. Water balance attributes from year 2003 according to Hauger and Binning (2006).

General attributes		
Catchment area [km^2]	A	89.9
Population [10^3]	Pop	548
Population density [*persons* km^{-2}]	$Pop_{density}$	6096
Mean rainfall depth [*mm* $year^{-1}$]	Pr	613
Water balance attributes		
Rainfall volume [$10^6\ m^3\ year^{-1}$]	$V_{rainfall}$	61.5
Supplied potable water [$10^6\ m^3\ year^{-1}$]	$V_{potable\ water}$	32.8
Treated wastewater [$10^6\ m^3\ year^{-1}$]	$\mathrm{V}_{\mathrm{wastewater}}$	60.1
Roof runoff to sewers [$m10^6.\ m^3\ year^{-1}$] ($V_{Theoretical\ maximum}$ *for Case 3)*	$V_{roof\ runoff}$	6.1
Flow from paved areas to sewers [$10^6\ m^3 year^{-1}$] ($V_{Theoretical\ maximum}$ *for Case 1 and 2)*	$V_{paved\ runoff}$	23.0

2.5.2 Case data

A water balance used for planning purposes (Table 1) has been established previously for Copenhagen (Hauger and Binning, 2006). The rainfall volumes presented in the water balance are considered typical for the current conditions. Rainfall volumes in the water balance (*V*'s in Table 1) are based on only one year of data and are slightly (12%) wetter than time series averages (*Pr* in Table 1). However, to maintain consistency it was chosen to base efficiency metrics on the water balance.

We chose four different rain series of 20 years duration with 1-min resolution data, which represent well the differences in mean annual precipitation within Denmark (Table 2).

Table 2. Overview of rain gauge data (see Jørgensen et al. 1998, for details about the rainfall monitoring system).

Station name	Silkeborg Vandværk	Kolding Renseanlæg	Kongens Enghave	Måløv Renseanlæg
Station number	5192	5251	5765	5600
Coordinates	56°09'44.0"N 9°33'36.3"E	55°29'21.5"N 9°29'14.2"E	55°38'44.5"N 12°32'02.9"E	55°45'40.2"N 12°19'08.7"E
Record period	1979-1998	1979-1998	1979-1998	1979--1998
Corrected Length [years]	17.10	17.30	17.25	17.13
Mean Annual Precipitation [mm]	720	765	615	610

2.5.3 Case SCMs

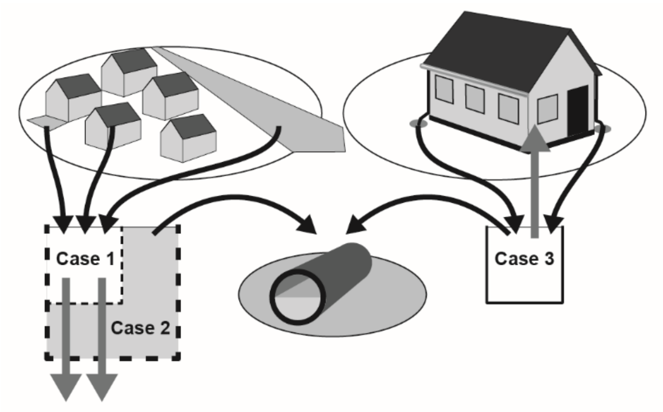

Figure 3. Illustration of the investigated SCMs. In Case 1 and 2 we consider infiltration of stormwater via soakaways with two different dimensions, and in Case 3 we consider a rainwater harvesting tank with subsequent indoor use. All three SCMs include overflow to a combined sewer system.

Case 1 (Figure 3) considers all impermeable areas of the city as catchment area. It considers soakaways dimensioned according to the Danish design guidelines for rainwater harvesting systems (Mikkelsen et al., 1999; Teknologisk Institut, 2002), which corresponds to a design for Point A, i.e. a design for rainfall events with return periods of up to 0.2 year.

Case 2 (Figure 3) is designed with the same catchment area as Case 1 but considering soakaways dimensioned according to the design guidelines of sewer systems, which corresponds to a design for Point B, i.e. a design for rainfall events with return periods of up to 10 years.

The stormwater infiltrated in cases 1 and 2 cannot be directly used to replace potable water and will therefore by definition gain an E_{pw} value of zero (the importance of increasing groundwater recharge is considered negligible).

Case 3 (Figure 3) considers rainwater harvesting tanks, where the water is used for flushing toilets. The use of the collected water entails more restrictions on the design than soakaways. We follow the Danish design guidelines (Mikkelsen et al., 1999; Teknologisk Institut, 2002) that allow water to be collected only from roofs. To avoid too long storage periods the system must be flushed regularly, hence a design for Point A is required (Teknologisk Institut, 2002). In Case 3, the SCM has the added value of replacing potable water, and thus has the potential for reducing potable water demand expressed in the metric E_{pw}.

In all cases, we assume that when the capacity of the SCMs is exceeded it overflows to the sewer system, which is designed for a return period of 10 years (Point B). For events exceeding Point B SCMs overflow to the surface.

3 Results

3.1 Event depths and accumulated rainfall volumes for each 3PA domain

The analysis of the historical rain records shows that the depth of events in the everyday domain (Point A) is approximately 20 mm (Figure 44a). For Point B and C the depths are 70 and 110 mm respectively. However, the main part of the accumulated annual rainfall falls within the everyday domain (75%) and the design domain (24%) (Figure 44b). An SCM designed for a return period of 0.2 years will thus manage 75% of the annual rainfall volume and a design for a return period of 10 years will manage approximately 99% of the annual rainfall volume (points A and B aggregated). This leaves virtually no volume in the extreme domain in terms of annual rainfall volume. The difference between aggregating rain in 3-hour and 24-hour events only changes the volume falling in the everyday domain (Point A) from approximately 80% to 70% and in the design domain (Point B) from approximately 20% to 30%, with the longer event aggregation allocating more water to the design domain (Point B). In contrast, the choice of event duration has negligible influence on the accumulated volume falling in the extreme domain (Point C) as this is always very small.

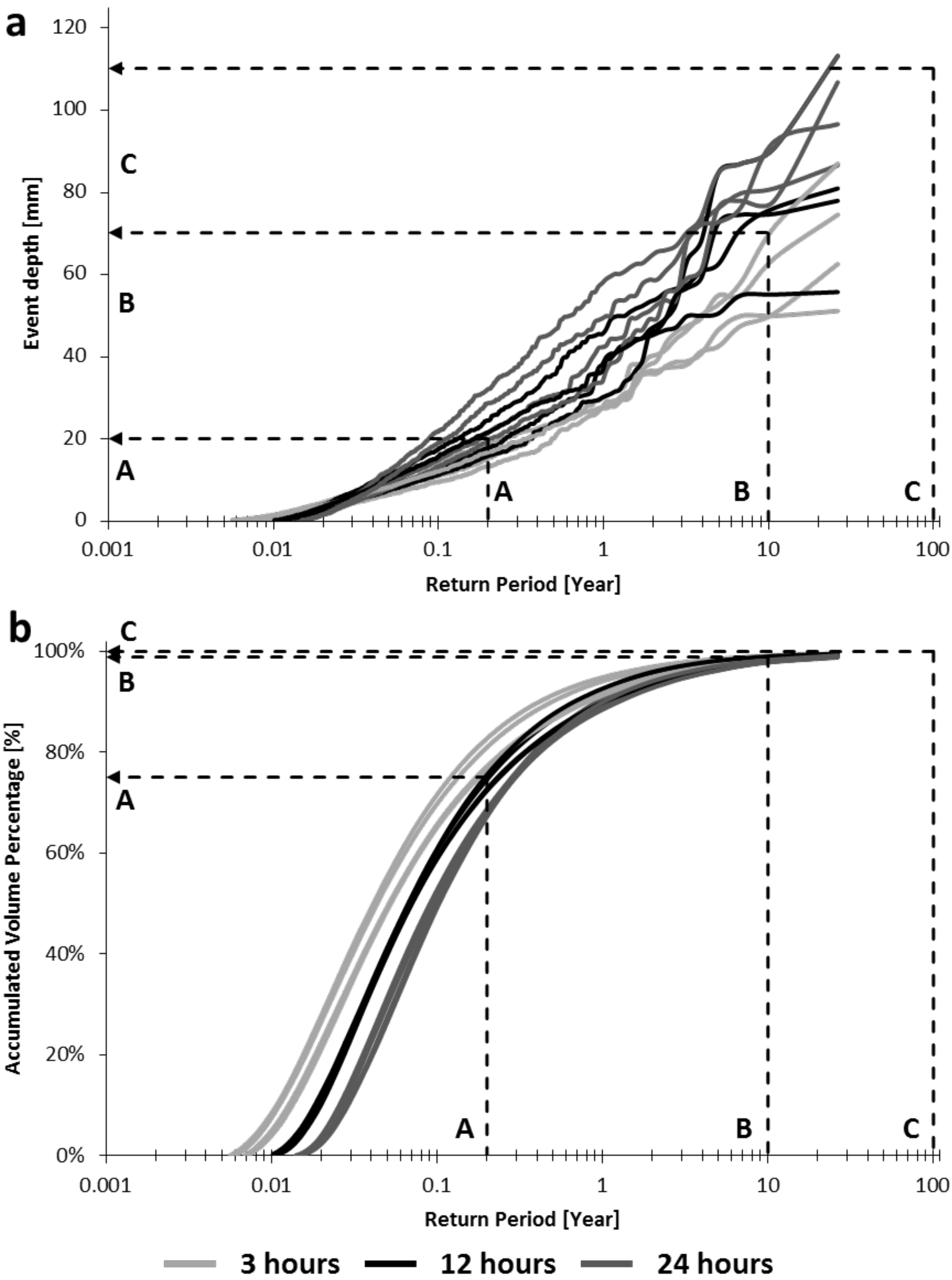

Figure 4. Usage of precipitation data to quantify the 3PA. a: Event depths ranked according to return period and marking of which event depths that constitute the different points in the 3PA. b: Volumetric percentages of total rainfall that falls within

the domains of the 3PA. Three different event definitions were included (3, 12 and 24 hour extremes), each calculated for four different rainfall series (from different parts of Denmark), resulting in 12 curves in total. The dotted vertical lines at return periods of 0.2 years and 10 years represent Point A and B of the 3PA (Figure 1). Point C is represented by average extrapolation of trends until 100 years.

Based on these findings, we define the three domains in quantitative terms for the Danish context as follows:

- Point A - The Everyday Domain: The defining event within this domain has a return period of 0.2 years and corresponds to a volume of 20 mm rainfall. The aggregated events in this domain account for 75% of the annual rainfall.
- Point B - The Design Domain: The defining event within this domain has a return period of 10 years and corresponds to a volume of 70 mm rainfall. The aggregated events in this domain account for 24% of the annual rainfall.
- Point C - The Extreme Domain: The defining event within this domain has a return period of 100 years and through extrapolation of data it is estimated that it corresponds to a volume of 110 mm rainfall. The aggregated events in this domain account for 1% of the annual rainfall.

In the supplementary material these results are depicted directly on the 3PA graph (Figure 1) as this in practise has proven to be very effective for communication purposes.

3.2 Theoretical efficiency distribution

Eq. 5 is used to calculate what happens when an SCM designed for one point is exposed to rainfall from other points. When a soakaway designed to store 20 mm of rain (Point

A) is exposed to a Point B event, i.e. 70 mm of rain, it will manage 20 mm (29%), and 50 mm (71%) will overflow from the structure. The inter-event time has little influence on the annual volumes defining the different domains (Figure 4b). The relationship between the points in the 3PA expressed in the $g_{i,j}$ fraction, has been calculated using the typical Danish rainfall events defined above (Table 3).

Table 3. Fraction of rainfall event depth that can be managed by a structure designed for a specific point in the domains A, B and C dependent on the rainfall input domain.

$g_{i,j}$		***j* = event type**		
		Point A - ***Everyday***	**Point B -** ***Design***	**Point C -** ***Extreme***
***i* = design criteria**	**Point A -** ***Everyday***	1.00	0.29	0.18
	Point B – ***Design***	1.00	1.00	0.64
	Point C - ***Extreme***	1.00	1.00	1.00

3.3 3PA efficiencies

The SCM in Case 1 (soakaways designed for Point A) manages 31% of the annual rainfall (E_r) corresponding to 19 mill. m^3 $year^{-1}$ (Table 4). The results reflect that the structure is able to control 83% of the total water volume entering the structure (E_{rmax}). Distributed in rainfall domains, the SCM manages 100% of the annual rainfall in Point A, 29% of the annual rainfall in Point B and 18% of the annual volume in Point C.

The SCM in Case 2 (soakaways designed for Point B) manages slightly more rainfall on annual basis with 37% (Table 4). This corresponds to almost 100% (99.6% actually) of the theoretical maximum volume (E_{rmax}), distributed with 100% for Point A and B rain events, and 64% for Point C events.

The efficiency in reducing combined sewage (E_{ww}) is notable for both Cases 1 and 2, with reduction percentages of 31-38%. Since infiltration does not affect the potable water demand, E_{pw} is zero for Cases 1 and 2.

The SCM in case 3 (rainwater harvesting for use in households) manages much less water than in Cases 1 and 2, with E_r of 9% (Table 4). The relative rainfall control efficiency (E_{rmax}) is equal to that in Case 1 with 83%, but note that this may be misleading since in our example the relevant catchment areas in case 3 comprise only roofs, and thus only 5.7 mill. m^3 $year^{-1}$, respectively, are managed in Case 3. Although the relative rainfall control (E_{rmax}) and the absolute volume managed in Case 3 are significantly smaller than in cases 1 and 2, the 9.4% reductions in combined sewage (E_{ww}) are still notable from the point of view of a wastewater treatment plant manager. Since the harvested rainwater replaces potable water, there is also a marked reduction in potable water demand (E_{pw} = 17%).

Table 4. Efficiency metrics for Cases 1 to 3 calculated using Eq. 2-6, given as percentages.

Copenhagen	**Case 1 (soakaway designed for Point A)**				**Case 2 (soakaway designed for Point B)**				**Case 3 (Harvesting and use designed for Point A)**			
3PA rainfall domains (points) Efficiencies [%]	**A**	**B**	**C**	**Total**	**A**	**B**	**C**	**Total**	**A**	**B**	**C**	**Total**
Volumetric rainfall control (E_r)	28	2.6	0.0068	31	28	9.0	0.24	37	8.4	0.77	0.020	9.2
Relative rainfall control (E_{rmax})	100	29	18	83	100	100	64	100	100	29	18	83
Potable water demand reduction (E_{pw})	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16	1.4	0.038	17
Wastewater production reduction (E_{ww})	29	2.6	0.070	31	29	9.2	0.24	38	8.6	0.79	0.021	9.4
Volume managed [mill. m^3 $year^{-1}$]	17	1.6	0.042	19	17	5.5	0.15	23	5.2	0.47	0.013	5.7

4 Discussion

The efficiency scores attained in the case study SCMs illustrate the conflict of goals described in the introduction between managing large volumes of water over time and managing single extreme events. Whether domain A, B, or C is the cause of concern is case specific and will depend on the context of the catchment in question (Lerer et al., 2015). For example, in some areas water conservation and reduction in potable water use is a main concern and driver for SCMs (Campisano and Modica, 2015; Londra et al., 2015). In other areas, the main concern may be limiting combined sewer overflows (Petrucci et al., 2012; Stovin et al., 2013) or to conserve the pre-development catchment water balance (Henrichs et al., 2016) and the river flow regime (Fletcher et al., 2013). Finally, other places mainly respond to increasing flood risks (Zhou et al., 2013). Common for the cases is that inclusion of SCMs in the urban water management system will influence the full water cycle and not only the component of main concern. This is where our proposed efficiency metrics and the 3PA may help decision makers to identify additional benefits or unexpected caveats of potential SCM setups.

From a volumetric point of view, all the SCMs analysed manage more than 83% of the annual rainfall in their catchment area, as expressed by the relative rainfall efficiency, E_{rmax}. From a resource perspective this is very satisfactory as the SCMs considerably ease the load on the wastewater treatment plant (assuming the catchments otherwise drain to a combined sewers system), and in Case 3 the SCM also considerably reduces potable water demand. In other words, this high overall efficiency of the SCMs, corresponding to a very high efficiency in the everyday domain, reflects that these SCMs perform well in terms of rainwater resource utilization.

However, the efficiency metrics scored in the two other 3PA domains, the design domain and the extreme domain, reveal that the SCMs we analysed are less promising in terms of flood risk mitigation. In Case 1 and 3 the SCMs manage 29% of the rainfall volume for Point B events and 18% for Point C events, on an annual basis. These numbers reflect an idealized situation where the entire storage capacity of the SCM is available at the onset of the rain event. In reality, the storage will rarely be fully available and the performance will be accordingly less efficient. An SCM dimensioned to hold 20 mm of rainfall will not always be empty at the onset of a rain event and can therefore not always manage all 20 mm. However, long term simulations indicate that this has little influence on the annual water balance (Locatelli et al., 2015) and the simplification is justified for citywide planning purposes. Efficiencies calculated using the 3PA domains demonstrate that the same SCM performs differently within the different rainfall domains. This is not necessarily evident to all professionals working with city infrastructure, yet it is crucial to understand when making decisions on investments in stormwater management systems.

Case 2 illustrates how the volume of soakaways needed to meet the design requirements of Point B is approximately three times larger than the volume needed to meet the requirements for Point A (Case 1). Yet, the annual volume managed by the larger SCM increases only 21% in our case (from 19 to 23 mill. m^3 $year^{-1}$).

When designing SCMs to reduce flood risk it is important to focus on the domain of extremes (Point C). One possible solution to improve the performance of SCMs in case of extreme rainfall events is to build in a mechanism that ensures all possible storage space is available at the onset of the rain event, e.g. based on a real-time control scheme (Han, 2013). This will give a higher efficiency for Point C (and potentially also for Point B), at the expense of the efficiency of Point A. In other words, keeping volume available for rare events will reduce the volume managed annually. Our approach facilitates a clear message to the non-technical decision maker: SCMs that exploit the full potential for managing the annual water balance (illustrated by the efficiency metrics of the everyday domain) will not perform optimally during all extreme events (illustrated by the efficiency metrics of the extreme domain). As such, the design of SCMs should explicitly take into account and balance the perceptions and findings in relation to the main problems in the analysed catchment.

While it may remain challenging to interpret the efficiencies for rainfall control (E_r and E_{rmax}), the efficiencies for reducing potable water demand and wastewater production have rather straight forward benefits. Reduction in potable water demand is a positive outcome in terms of environmental protection of the water resource and reduced burden on production and distribution of potable water. Reduction in wastewater production saves operational costs at the wastewater treatment plant in case of combined sewer systems, and may even in some cases delay or eliminate a need for expanding the wastewater treatment plant. In catchments with frequent overflows from a combined sewer system, the environmental benefit of reduced wastewater production may also be significant.

Note that many SCMs offer additional benefits not considered here. For example, SCMs that add blue-green elements like swales or stormwater ponds may increase biodiversity, aesthetical value and recreational value (Zhou et al., 2013). Holistic assessments of SCMs should go beyond our proposed metrics and include such additional benefits as well.

5 Conclusions

Our method facilitates the analysis of Stormwater Control Measures (SCMs) impact on the urban water balance in three rainfall domains of the Three Points Approach (3PA): A) the everyday domain, B) the urban stormwater pipe design domain, and C) the pluvial flood mitigation, or extreme, domain.

The method is useful to assess and communicate:

- which rainfall domain a given SCM is most suitable for,
- how much rain an SCM can manage when designed and re-designed for different design criteria, and
- how an SCM responds when its design criterion is exceeded.

The domains of the 3PA have been quantified for Danish conditions in terms of return periods and rain depth. Based on this quantification, it was found that SCMs such as rainwater harvesting or soakaways, designed to manage 100% of the rainfall from the everyday domain, will manage only 29% of the rainfall from the design domain and just 18% of rainfall from the extreme domain. This indicates that SCMs are not very effective means to reduce the risk of flooding. On the other hand, the efficiencies show that by harvesting only a minor fraction of the total rainfall (9%), the annual volumes conveyed to wastewater treatment can be reduced with 12% and the potable water demand can be reduced by up to 19%. This suggests that large scale implementation of SCMs may have substantial benefits in relation to resource utilization.

We believe that the simplicity of our method and the transparency of the results make it well suited to communicate the evaluation criteria used by engineers to other stakeholders involved in the decision process for SCMs such as urban planners and politicians.

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