



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

Sørup, Hjalte Jomo Danielsen; Lerer, Sara Maria; Arnbjerg-Nielsen, Karsten; Mikkelsen, Peter Steen; Rygaard, Martin

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

4 Hjalte Jomo Danielsen Sørup^{1,2*}, Sara Maria Lerer¹, Karsten Arnbjerg-
5 Nielsen^{1,2}, Peter Steen Mikkelsen^{1,3} and Martin Rygaard^{1,3}

6 ¹*Urban Water Systems Section, Department of Environmental Engineering, Technical*
7 *University of Denmark, Bygningstorvet Building 115, 2800 Lyngby, Denmark.*

8 ²*GDSI, Global Decision Support Initiative, Technical University of Denmark,*
9 *Produktionstorvet, Building 424, 2800 Lyngby, Denmark*

10 ³*Water DTU, Center for Water Activities at DTU, Technical University of Denmark,*
11 *Bygningstorvet Building 115, 2800 Lyngby, Denmark.*

12 * Corresponding author. Email: hjds@env.dtu.dk

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

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

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

39 **1 Introduction**

40 Management of urban stormwater, i.e. rainwater that runs off paved urban areas, is
41 complex because of conflicting needs and objectives. Traditional stormwater
42 management technology in the form of sewers is installed with the aim of draining
43 stormwater efficiently to protect human health and human assets, but this practice often
44 disturbs the natural water cycle and has a multitude of other detrimental environmental
45 impacts (Schuster et al., 2005). Alternative stormwater management has gained
46 increased attention in recent years due to different drivers such as aging infrastructure, a

47 wish for more cyclical rather than linear systems (Chocat et al., 2007), and increases in
48 size and occurrence of extreme rainfall due to anthropogenic climatic changes
49 (Arnbjerg-Nielsen et al., 2013). A suite of newer structural and non-structural practices
50 for stormwater management has emerged, reflecting the different perspectives involved
51 and the needs for driving the stormwater profession in new directions. These are in the
52 following called stormwater control measures (SCMs) and represent technologies such
53 as stormwater best management practices (BMPs), green infrastructure (GI), low impact
54 development (LID), sustainable urban drainage systems/sustainable drainage systems
55 (SUDS/SuD), and water sensitive urban design (WSUD) (Fletcher et al., 2015). We
56 use SCMs in this article to refer to any combinations of practices, structures, or
57 implemented technologies that seek to reduce the negative environmental impacts of
58 sewer based stormwater systems. This is in line with the definition given by the
59 Committee on Reducing Stormwater Discharge Contributions to Pollution (2009).

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

68 Efficiency of an SCM expressed as a fraction of the total rainwater volume over
69 extended periods of time, e.g. a year, can be misleading if used in a flooding context.
70 For example, stating that an SCM controlling 60% or even 99% of the annual rainwater
71 volume will reduce the risk of urban flooding (see e.g. Armson et al., 2013 for an

72 example) may be misleading as the remaining 1% of the rainwater volume is composed
73 of the extreme events with heavy peaks that exceed the design criteria for the SCM in
74 question and cause floods. Stovin et al. (2013) used a lumped sewer model to show that
75 the annual number of Combined Sewer Overflows (CSOs) can be reduced using
76 “*aggressive implementation of SuDS*”. The analysis considered catchments with very
77 frequent CSOs (29-59 per year) and the rainfall events analysed had return periods of
78 only two and four years. More extreme rainfall events are discussed in the study but no
79 clear conclusions are provided. Locatelli et al. (2014) and Yang et al. (2015) both
80 modelled and experimented with green roofs. Locatelli et al. (2014) validated a model
81 for three different green roofs and subsequently evaluated their performance with
82 respect to retaining water for a range of observed rainfall events. Yang et al. (2015)
83 experimented with a wide range of precipitation input to a similar model to explore the
84 performance under extreme conditions. Both studies showed a clearly decreasing
85 performance as events become larger.

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

93 To provide consistent reporting and avoid confusing communication about the
94 efficiency of SCMs, we suggest a method for reporting the efficiency of different
95 approaches based on ‘rainfall domains’. Our method extends the Three Points Approach
96 (3PA) presented by Fratini et al. (2012), which defined three distinct decision domains,

97 each governed by different professionals, affected by different stakeholders and
98 subjected to different values. We redefine the three domains from a hydrologic
99 perspective in terms of rainfall return periods relevant within the urban water cycle.
100 This allows calculating quantitative efficiencies for a given SCM in each domain with
101 respect to each flow, resulting in a matrix of metrics that together characterise the
102 performance of the given SCM comprehensively and clearly. Our proposed method
103 aims to facilitate better communication between different stakeholders about the
104 efficiency of different stormwater management strategies by answering questions like:
105 *“under what circumstances may rainwater harvesting systems and other stormwater*
106 *control measures be expected to contribute efficiently to (A) rainwater resource*
107 *utilisation, (B) urban storm drainage pipe capacity and (C) pluvial flood mitigation?”*.
108 The method is applied to three theoretical SCM strategies for the City of Copenhagen,
109 Denmark

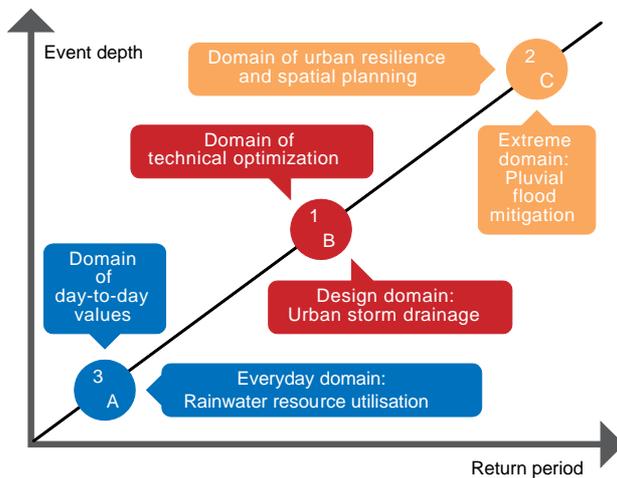
110 **2 Methods and data**

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

116 **2.1 Defining the domains of the 3PA**

117 In the original definition of The Three Points Approach (3PA) Fratini et al. (2012)
118 delineated three distinct domains in which decisions related to stormwater management
119 are made. They illustrated how the domains relate to distinct types of rainfall events that
120 occur with different magnitude and return period, cf. Figure 1. Adopting an urban

121 drainage engineer viewpoint, they labelled these typical rain events decision points from
 122 1 to 3. *Point 1* refers to the most important point for the urban drainage engineer, the
 123 “what is my responsibility”-point, *Point 2* refers to the second most important point, the
 124 “what happens when the system capacity is exceeded”-point, and *Point 3* refers to the
 125 least important point, the “how could we do something alternative with the rainwater”-
 126 point. However, in order of increasing magnitude of rain events, Fratini et al.’s domains
 127 come in the sequence 3, 1, 2 and for quantitative evaluations, this numbering is less
 128 intuitive. Hence, we renamed the Points A, B and C, where the point corresponding to
 129 the smallest and most frequent events is named A and the point corresponding to the
 130 largest and rarest events is named C (Figure 1). This modification to the 3PA is relevant
 131 since SCMs perform differently for varying magnitudes of rain events. Furthermore, we
 132 redefine the axes to reflect rainfall magnitude (vertical axis) and rainfall return period
 133 (horizontal axis), allowing a quantification of the three points based on historical
 134 rainfall time series.



135

136 Figure 1. Conceptual definition of the 3PA domains. Fratini et al. (2012) defined the
 137 3PA in domains 3, 1, 2 and we modified the labelling to A, B, and C in the order of
 138 increasing return periods.

139

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

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

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

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

161 **2.2 Quantifying the domains of the 3PA**

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

170
$$T_m = (T_{obs} + 0.4) / (m - 0.3) \quad (1)$$

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

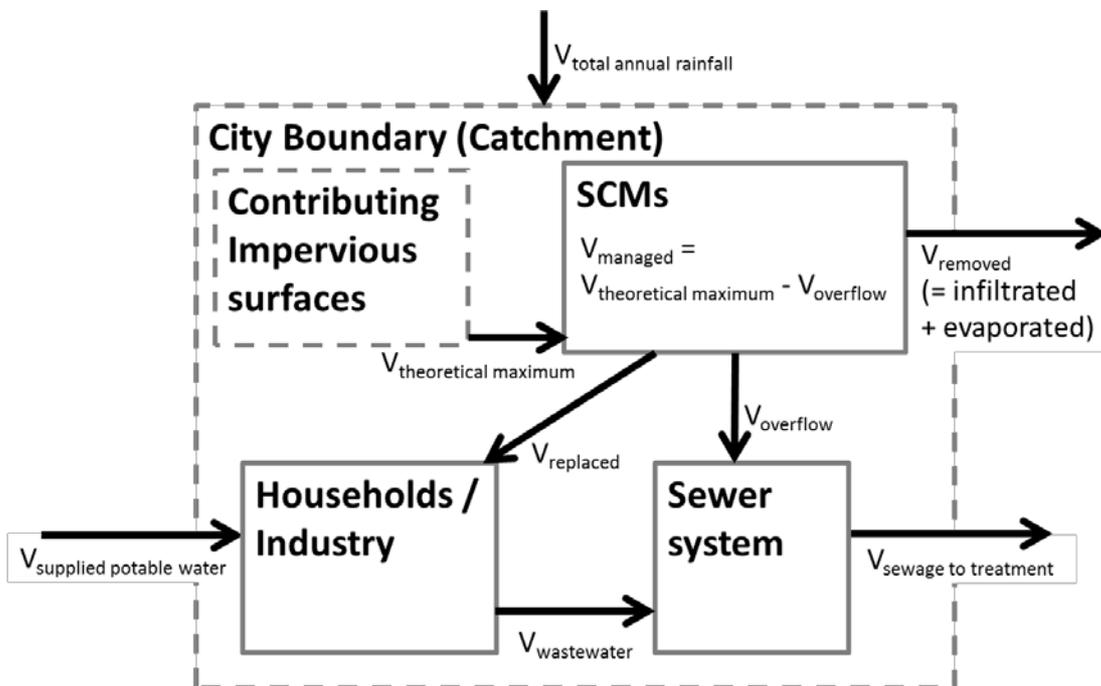
173 We chose a characteristic return period for each domain based on prevailing design
174 standards in Denmark. The Danish design criteria for rainwater harvesting and usage
175 were used to define Point A as $T=0.2$ years (Teknologisk Institut, 2002). The
176 recommendation of the The Water Pollution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

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

186 **2.3 Defining efficiencies of SCMs**

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

192



193

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

195

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

198
$$E_r = V_{managed} / V_{total\ annual\ rainfall} \quad (2)$$

199 $V_{total\ annual\ rainfall}$ is the direct input flow to the city wide water balance and E_r thus

200 depends directly on the spatial extent of the considered area. E_{rmax} is the spatially

201 independent efficiency metric expressing the ratio between managed volume ($V_{managed}$)
 202 and the volume of rainfall received by the proposed SCM ($V_{theoretical\ maximum}$):

$$203 \quad E_{rmax} = V_{managed} / V_{theoretical\ maximum} \quad (3)$$

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

$$206 \quad E_{pw} = V_{replaced} / V_{supplied\ potable\ water} \quad (4)$$

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

$$209 \quad E_{ww} = V_{removed} / V_{sewage\ to\ treatment} \quad (5)$$

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

212 **2.4 Conditioning the SCM efficiencies on the 3PA domains**

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

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

$$220 \quad E_r^{ji} = f_j g_{i,j} E_r \quad (6)$$

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

224 $g_{i,j}$ will be 1 for the design point and for any point below (with lower return periods) and
225 < 1 for any point above (with larger return periods); how much lower is determined
226 using historical rainfall records.

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

235 ***2.5 The case study***

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

239 ***2.5.1 Copenhagen municipality***

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

244

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

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

247

248 2.5.2 Case data

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

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

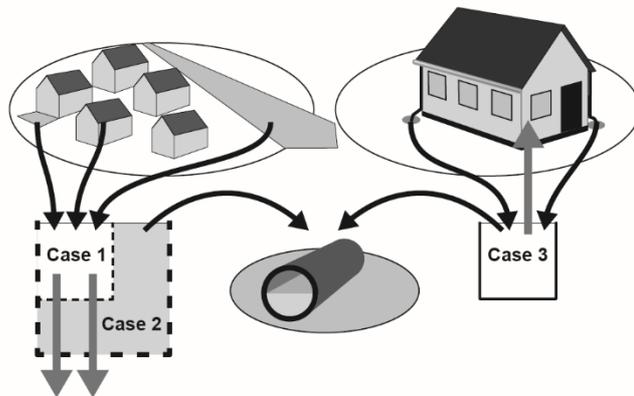
258

259 Table 2. Overview of rain gauge data (see Jørgensen et al. 1998, for details about the
 260 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

261

262 2.5.3 Case SCMs



263

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

268

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

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

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

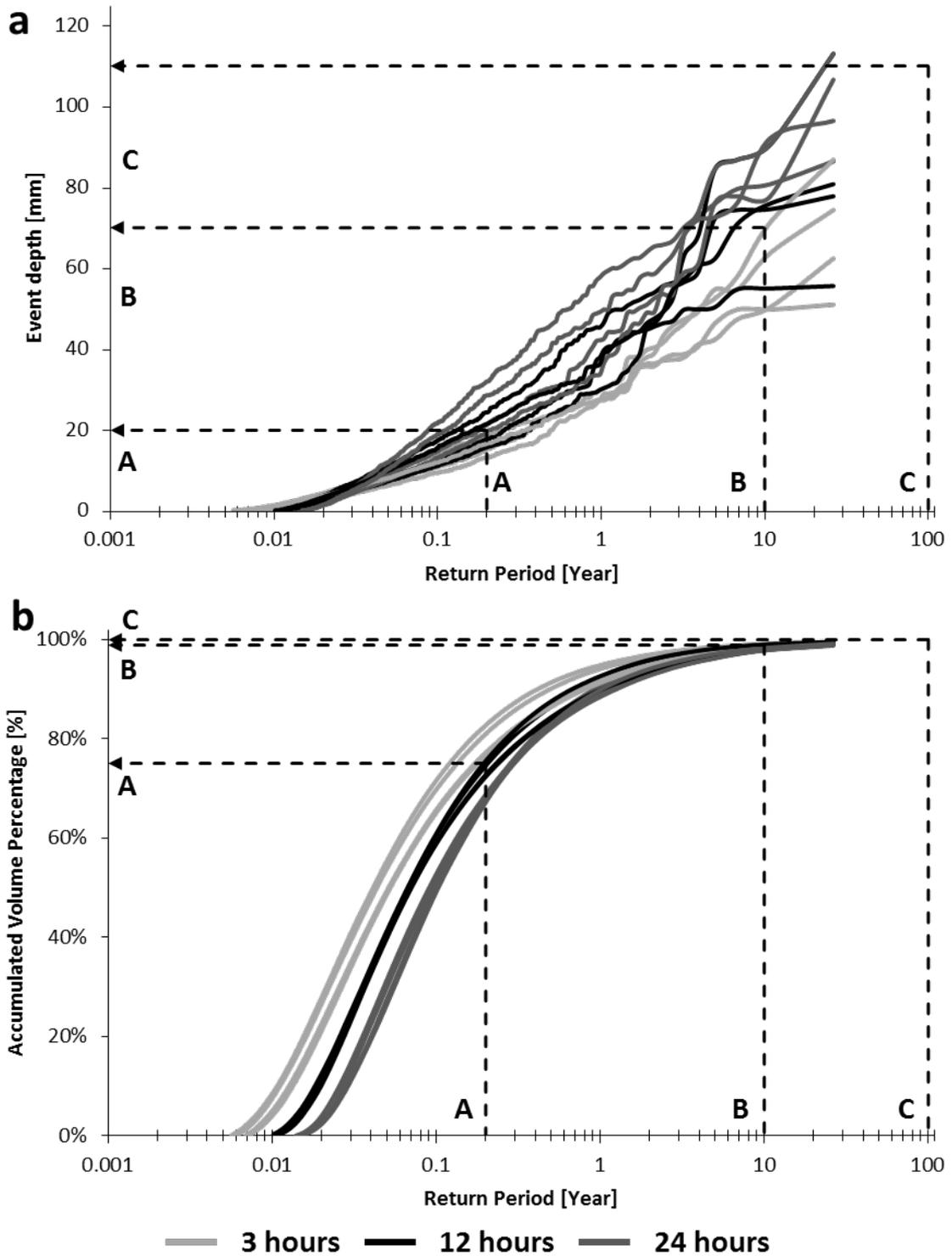
281 Case 3 (Figure 3) considers rainwater harvesting tanks, where the water is used for
282 flushing toilets. The use of the collected water entails more restrictions on the design
283 than soakaways. We follow the Danish design guidelines (Mikkelsen et al., 1999;
284 Teknologisk Institut, 2002) that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

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

292 **3 Results**

293 **3.1 *Event depths and accumulated rainfall volumes for each 3PA domain***

294 The analysis of the historical rain records shows that the depth of events in the everyday
295 domain (Point A) is approximately 20 mm (Figure 44a). For Point B and C the depths
296 are 70 and 110 mm respectively. However, the main part of the accumulated annual
297 rainfall falls within the everyday domain (75%) and the design domain (24%) (Figure
298 44b). An SCM designed for a return period of 0.2 years will thus manage 75% of the
299 annual rainfall volume and a design for a return period of 10 years will manage
300 approximately 99% of the annual rainfall volume (points A and B aggregated). This
301 leaves virtually no volume in the extreme domain in terms of annual rainfall volume.
302 The difference between aggregating rain in 3-hour and 24-hour events only changes the
303 volume falling in the everyday domain (Point A) from approximately 80% to 70% and
304 in the design domain (Point B) from approximately 20% to 30%, with the longer event
305 aggregation allocating more water to the design domain (Point B). In contrast, the
306 choice of event duration has negligible influence on the accumulated volume falling in
307 the extreme domain (Point C) as this is always very small.



308

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

312 the domains of the 3PA. Three different event definitions were included (3, 12 and 24
313 hour extremes), each calculated for four different rainfall series (from different parts of
314 Denmark), resulting in 12 curves in total. The dotted vertical lines at return periods of
315 0.2 years and 10 years represent Point A and B of the 3PA (Figure 1). Point C is
316 represented by average extrapolation of trends until 100 years.

317

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

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

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

333 ***3.2 Theoretical efficiency distribution***

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

336 A) is exposed to a Point B event, i.e. 70 mm of rain, it will manage 20 mm (29%), and
337 50 mm (71%) will overflow from the structure. The inter-event time has little influence
338 on the annual volumes defining the different domains (Figure 4b). The relationship
339 between the points in the 3PA expressed in the $g_{i,j}$ fraction, has been calculated using
340 the typical Danish rainfall events defined above (Table 3).

341

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

g_{ij}		$j = \text{event type}$		
		Point A - <i>Everyday</i>	Point B - <i>Design</i>	Point C - <i>Extreme</i>
$i = \text{design criteria}$	Point A - <i>Everyday</i>	1.00	0.29	0.18
	Point B - <i>Design</i>	1.00	1.00	0.64
	Point C - <i>Extreme</i>	1.00	1.00	1.00

344 3.3 3PA efficiencies

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

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

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

357 The SCM in case 3 (rainwater harvesting for use in households) manages much less
 358 water than in Cases 1 and 2, with E_r of 9% (Table 4). The relative rainfall control
 359 efficiency (E_{rmax}) is equal to that in Case 1 with 83%, but note that this may be
 360 misleading since in our example the relevant catchment areas in case 3 comprise only

361 roofs, and thus only 5.7 mill. m³ year⁻¹, respectively, are managed in Case 3. Although
362 the relative rainfall control (E_{rmax}) and the absolute volume managed in Case 3 are
363 significantly smaller than in cases 1 and 2, the 9.4% reductions in combined sewage
364 (E_{ww}) are still notable from the point of view of a wastewater treatment plant manager.
365 Since the harvested rainwater replaces potable water, there is also a marked reduction in
366 potable water demand ($E_{pw} = 17\%$).

368 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)			
	A	B	C	Total	A	B	C	Total	A	B	C	Total
3PA rainfall domains (points)												
Efficiencies [%]												
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. m³ year⁻¹]	17	1.6	0.042	19	17	5.5	0.15	23	5.2	0.47	0.013	5.7

369 **4 Discussion**

370 The efficiency scores attained in the case study SCMs illustrate the conflict of goals
371 described in the introduction between managing large volumes of water over time and
372 managing single extreme events. Whether domain A, B, or C is the cause of concern is
373 case specific and will depend on the context of the catchment in question (Lerer et al.,
374 2015). For example, in some areas water conservation and reduction in potable water
375 use is a main concern and driver for SCMs (Campisano and Modica, 2015; Londra et
376 al., 2015). In other areas, the main concern may be limiting combined sewer overflows
377 (Petrucci et al., 2012; Stovin et al., 2013) or to conserve the pre-development catchment
378 water balance (Henrichs et al., 2016) and the river flow regime (Fletcher et al., 2013).
379 Finally, other places mainly respond to increasing flood risks (Zhou et al., 2013).
380 Common for the cases is that inclusion of SCMs in the urban water management system
381 will influence the full water cycle and not only the component of main concern. This is
382 where our proposed efficiency metrics and the 3PA may help decision makers to
383 identify additional benefits or unexpected caveats of potential SCM setups.

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

392 However, the efficiency metrics scored in the two other 3PA domains, the design
393 domain and the extreme domain, reveal that the SCMs we analysed are less promising

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

407 Case 2 illustrates how the volume of soakaways needed to meet the design requirements
408 of Point B is approximately three times larger than the volume needed to meet the
409 requirements for Point A (Case 1). Yet, the annual volume managed by the larger SCM
410 increases only 21% in our case (from 19 to 23 mill. m³ year⁻¹).

411 When designing SCMs to reduce flood risk it is important to focus on the domain of
412 extremes (Point C). One possible solution to improve the performance of SCMs in case
413 of extreme rainfall events is to build in a mechanism that ensures all possible storage
414 space is available at the onset of the rain event, e.g. based on a real-time control scheme
415 (Han, 2013). This will give a higher efficiency for Point C (and potentially also for
416 Point B), at the expense of the efficiency of Point A. In other words, keeping volume
417 available for rare events will reduce the volume managed annually. Our approach
418 facilitates a clear message to the non-technical decision maker: SCMs that exploit the

419 full potential for managing the annual water balance (illustrated by the efficiency
420 metrics of the everyday domain) will not perform optimally during all extreme events
421 (illustrated by the efficiency metrics of the extreme domain). As such, the design of
422 SCMs should explicitly take into account and balance the perceptions and findings in
423 relation to the main problems in the analysed catchment.

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

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

439 **5 Conclusions**

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

444 The method is useful to assess and communicate:

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

449 The domains of the 3PA have been quantified for Danish conditions in terms of return
450 periods and rain depth. Based on this quantification, it was found that SCMs such as
451 rainwater harvesting or soakaways, designed to manage 100% of the rainfall from the
452 everyday domain, will manage only 29% of the rainfall from the design domain and just
453 18% of rainfall from the extreme domain. This indicates that SCMs are not very
454 effective means to reduce the risk of flooding. On the other hand, the efficiencies show
455 that by harvesting only a minor fraction of the total rainfall (9%), the annual volumes
456 conveyed to wastewater treatment can be reduced with 12% and the potable water
457 demand can be reduced by up to 19%. This suggests that large scale implementation of
458 SCMs may have substantial benefits in relation to resource utilization.

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

463 **References**

464 Armson, D., Stringer, P., Ennos, A.R. (2013). The effect of street trees and amenity grass on
465 urban surface water runoff in Manchester, UK. *Urban Forestry & Urban Greening*, 12(3),
466 pp. 282-286. doi: 10.1016/j.ufug.2013.04.001.

467 Arnbjerg-Nielsen, K., Willems, P., Olsson, J., Beecham, S., Pathirana, A., Gregersen, I.B.,
468 Madsen, H., Nguyen, V-T-V. (2013). Impacts of climate change on rainfall extremes and
469 urban drainage systems: a review. *Water Science and Technology*, 68(1), pp. 16-28. doi:
470 10.2166/wst.2013.251.

471 Campisano, A. and Modica, C. (2015). Selecting time scale resolution to evaluate water saving
472 and retention potential of rainwater harvesting tanks. *Journal of Hydroinformatics*, 17, pp.
473 331–346. doi:10.2166/hydro.2015.022.

474 Chocat, B., Ashley, R., Marsalek, J., Matos, M. R., Rauch, W., Schilling, W. & Urbonas, B.
475 (2007). Toward the sustainable management of urban storm-water. *Indoor and built
476 environment*, 16(3), pp. 273–285. doi: 10.1177/1420326X07078854.

477 Committee on Reducing Stormwater Discharge Contributions to Water Pollution (2009). Urban
478 Stormwater Management in the United States. National Academies Press, Washington DC.
479 ISBN: 9780309125390.

480 Fletcher, T.D., Andrieu, H. and Hamel, P. (2013). Understanding, management and modelling
481 of urban hydrology and its consequences for receiving waters: A state of the art. *Advances in
482 Water Resources*, 51, pp. 261–279. doi:10.1016/j.advwatres.2012.09.001.

483 Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S.,
484 Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P.S., Rivard, G.,
485 Uhl, M., Dagenais, D. and Viklander, M. (2015). SUDS, LID, BMPs, WSUD and more –
486 The evolution and application of terminology surrounding urban drainage. *Urban Water
487 Journal*, 12(7), pp. 525–542. doi:10.1080/1573062x.2014.916314.

488 Fratini, C.F., Geldof, G.D., Kluck, J and Mikkelsen, P.S. (2012). Three Points Approach (3PA)
489 for urban flood risk management: A tool to support climate change adaptation through
490 transdisciplinarity and multifunctionality. *Urban Water Journal*, 9(5) pp. 317. doi:
491 10.1080/1573062X.2012.668913.

- 492 Han, M. (2013) Progress of multipurpose and proactive rainwater management in Korea.
493 *Environmental Engineering Research*, 18(2), pp. 65-69. doi:10.4491/eer.2013.18.2.065
- 494 Hauger, M.B. and Binning, P.J. (2006). Integrated management of water and wastewater in
495 Copenhagen: Mapping of present resources and use and existing cleaning technologies for
496 water and wastewater [*Integreret håndtering af vand og spildevand i København:
497 Overordnet kortlægning af nuværende ressourcer og forbrug, samt eksisterende
498 renseteknologier inden for vand- og spildevand*]. DTU Environment. In Danish.
- 499 Henrichs, M., Langner, J. and Uhl, M. (2016). Development of a simplified urban water balance
500 model (WABILA). *Water Science and Technology*, doi:10.2166/wst.2016.020.
- 501 Jørgensen, H.K., Rosenørn, S., Madsen, H. and Mikkelsen, P.S. (1998). Quality control of rain
502 data used for urban runoff systems. *Water Science and Technology* 37(11) pp. 113-120. doi:
503 10.1016/S0273-1223(98)00323-0.
- 504 Kenway, S., Gregory, A., and McMahon, J. (2011). Urban Water Mass Balance Analysis.
505 *Journal of Industrial Ecology*, 15(5), 693-706. doi:10.1111/j.1530-9290.2011.00357.x.
- 506 Lerer, S.M., Arnbjerg-Nielsen, K., and Mikkelsen, P.S. (2015). A Mapping of Tools for
507 Informing Water Sensitive Urban Design Planning Decisions—Questions, Aspects and
508 Context Sensitivity. *Water*, 7(3), pp. 993–1012. doi:10.3390/w7030993.
- 509 Locatelli, L., Gabriel, S., Mark, O., Mikkelsen, P.S., Arnbjerg-nielsen, K., Taylor, H.,
510 Bockhorn, B., Larsen, H., Kjølby, M.J., Blicher, A.S. and Binning, P.J. (2015). Modelling
511 the impact of retention-detention units on sewer surcharge and peak and annual runoff
512 reduction. *Water Science and Technology*, 71, pp. 898–903. doi:10.2166/wst.2015.044.
- 513 Locatelli, L., Mark, O., Mikkelsen, P. S., Arnbjerg-Nielsen, K., Jensen, M. B., & Binning, P. J.
514 (2014). Modelling of green roof hydrological performance for urban drainage applications.
515 *Journal of Hydrology*, 519(Part D), pp. 3237-3248. 10.1016/j.jhydrol.2014.10.030.

516 Londra, P.A., Theocharis, A.T., Baltas, E. and Tsihrintzis, V.A. (2015). Optimal Sizing of
517 Rainwater Harvesting Tanks for Domestic Use in Greece. *Water Resources Management*,
518 29, pp. 4357–4377. doi:10.1007/s11269-015-1064-1.

519 Madsen, H., Arnbjerg-Nielsen, K. and Mikkelsen, P.S. (2009). Update of regional intensity-
520 duration-frequency curves in Denmark: Tendency towards increased storm intensities.
521 *Atmospheric Research* 92(3), pp. 343-349. doi: 10.1016/j.atmosres.2009.01.013.

522 Mikkelsen, P.S., Adeler, O.F., Albrechtsen, H.-J. and Henze, M. (1999). Collected rainfall as a
523 water source in Danish households – What is the potential and what are the costs? *Water*
524 *Science and Technology*, 39(5) pp. 49-56. doi: 10.1016/S0273-1223(99)00086-4.

525 Petrucci, G., Deroubaix, J.-F., de Gouvello, B., Deutsch, J.-C., Bompard, P. and Tassin, B.
526 (2012). Rainwater harvesting to control stormwater runoff in suburban areas. An
527 experimental case-study. *Urban Water Journal*, 9, pp. 45–55. doi:
528 10.1080/1573062X.2011.633610.

529 Rosbjerg, D. (1988). *Defence of the median plotting position*. Progress Report - Institute of
530 Hydrodynamics and Hydraulic Engineering, Technical University of Denmark, (66), 17–28.

531 Schuster, W.D., Bonta, J., Thurston, H., Warnemuende, E. and Smith, D.R. (2005) Impacts of
532 impervious surface on watershed hydrology: a review. *Urban Water Journal*, 2(4). doi:
533 10.1080/15730620500386529.

534 Stovin, V.R., Moore, S.L., Wall, M. and Ashley, R.M. (2013) The potential to retrofit
535 sustainable drainage systems to address combined sewer overflow discharges in the Thames
536 Tideway catchment. *Water and Environment Journal*, 27(2), pp. 216-228. doi:
537 10.1111/j.1747-6593.2012.00353.x.

538 Teknologisk Institut (2002) Use of rainwater for toilet flushing and laundry in households [*Brug*
539 *af regnvand til wc-skyl og vaskemaskiner i boliger*], Rørcenter-anvisning 003, 2. udgave. In
540 Danish.

- 541 Water Pollution Committee of the Society of Danish Engineers (2005) Script 27 – Practical
542 function of urban drainage systems during rain [*SKRIFT 27 - Funktionspraksis for*
543 *afløbssystemer under regn*]. In Danish
- 544 Yang, W.-Y., Li, D., Sun, T., and Ni, G.-H. (2015). Saturation-excess and infiltration-excess
545 runoff on green roofs. *Ecological Engineering*, 74, 327–336.
546 doi:10.1016/j.ecoleng.2014.10.023
- 547 Zhou, Q., Panduro, T.E., Thorsen, B.J. and Arnbjerg-Nielsen, K. (2013). Adaption to Extreme
548 Rainfall with Open Urban Drainage System: An Integrated Hydrological Cost-Benefit
549 Analysis. *Environmental Management*, 51(3), 586-601. doi: 10.1007/s00267-012-0010-8.