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Modelling the impact of retention-detention units on sewer surcharge and peak and annual runoff reduction

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ABSTRACT

Stormwater management using Water Sensitive Urban Design (WSUD) is expected to be part of future drainage systems. This paper aims to model the combination of local retention units, such as soakaways, with subsurface detention units. Soakaways are employed to reduce (by storage and infiltration) peak and volume stormwater-runoff, however large retention volumes are required for a significant peak reduction. Peak runoff can therefore be handled by combining detention units with soakaways. This paper models the impact of retrofitting retention-detention units for an existing urbanized catchment in Denmark.

The impact of retrofitting a retention-detention unit of 3.3 m³/100m² (volume/impervious-area) was simulated for a small catchment in Copenhagen using MIKE URBAN. The retention-detention unit was shown to prevent flooding from the sewer for a 10-years rainfall event. Statistical analysis of continuous simulations covering 22 years showed that annual stormwater-runoff was reduced by 68-87%, and that the retention volume was on average 53% full at the beginning of rain events. The effect of different retention-detention volume combinations was simulated and results showed that allocating 20-40% of a soakaway volume to detention would significantly increase peak runoff reduction with a small reduction in the annual runoff.

Keywords

Detention; modelling; soakaways; Water Sensitive Urban Design

INTRODUCTION

Water Sensitive Urban Design (WSUD) aims at improving stormwater management and can be part of climate change adaptation strategies (Wong and Brown, 2009). Soakaways coupled with detention units, referred to as retention-detention units, increase groundwater recharge and reduce annual stormwater-runoff, pipe surcharge and Combined Sewer Overflows (CSOs).

Existing hydrological models that include WSUD elements are presented by Elliott and Trowsdale, 2007.

Several studies have presented models for the hydrological performance of single soakaways (Roldin et al., 2013; Roldin et al., 2012; Freni et al., 2009; Warnaars et al., 1999). These models were validated against either observed data or physical based models and then used for short term predictions of runoff from single soakaways.

48 Other studies have modeled the impact of implementing soakaways at catchment scale
49 (Roldin et al., 2012; Maimone et al., 2011; Antia, 2008), examining the effect on CSOs and
50 groundwater response. None of these studies have combined detention volumes to soakaways
51 and statistically quantified the continuous hydrological performance of retention-detention
52 units.

53 The aim of this study was to model the impact of retention-detention units on sewer
54 surcharge and annual runoff reduction. Moreover, the water content of storage units at the
55 beginning of rain events was estimated in order to determine the proper initial conditions
56 when modelling single events. Further, we model how different retention-detention volume
57 combinations affect annual and peak runoff reduction in order to assist in combined
58 soakaway-detention system design.

59

60 TOOLS AND METHODS

61 The retention-detention unit

62 Figure 1 shows the retention-detention unit that consists of the following elements:

- 63 • Water inlet. A pipe that diverts stormwater runoff into the retention-detention unit.
- 64 • Retention volume (Soakaway). A volume aimed for storage and infiltration.
- 65 • Detention storage. A volume aimed to delay peak flows.
- 66 • Overflow pipes. Pipes diverting water from the storage to the sewer system in case of
67 overflow.
- 68 • Valve. To control the maximum flow rate from the detention storage to the sewer
69 system.

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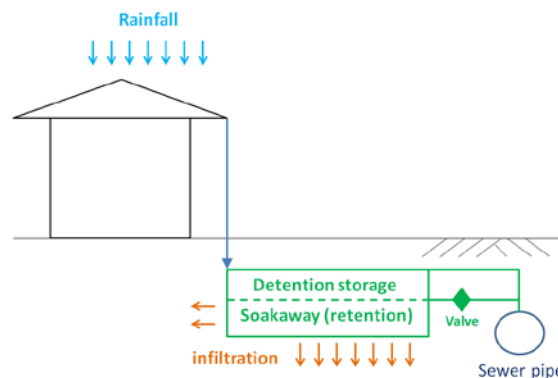


Figure 1. The retention-detention unit.

72 The retention-detention unit design

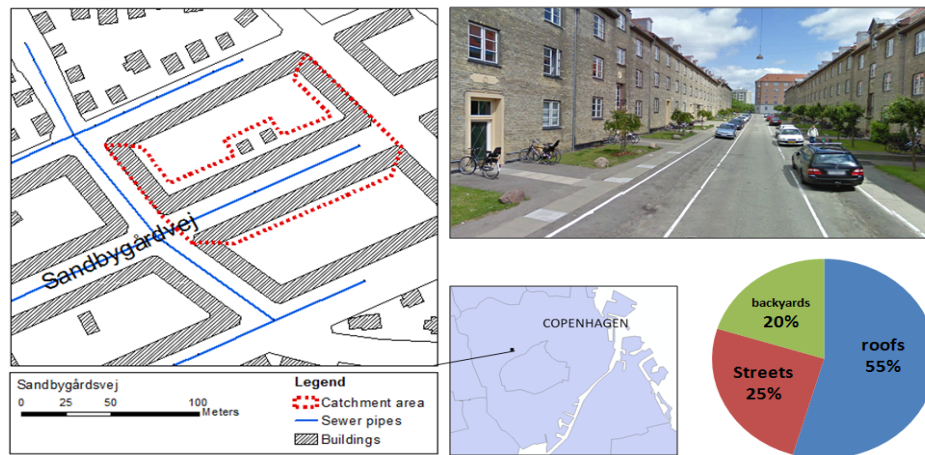
73 The retention-detention unit consists of a detention volume above a soakaway volume. The
74 soakaway aims to reduce annual runoff and the detention storage aims to reduce peak
75 overflow to the sewer. Soakaway and detention volumes are designed using Danish design
76 tools (Petersen et al., 1995). The design aims at accommodating the stormwater volume
77 accumulated during design events with a specified return period.

78

79 The case study area

80 The street of Sandbygårdvej is located in Copenhagen (Denmark) and is served by a
81 combined sewer system (Figure 2). The reduced (impermeable) catchment area connected to
82 the local sewer pipe is 0.67 hectares consisting of 55% roofs, 20% front and backyards and
83 25% street and sidewalks. Sandbygårdvej lies on a topographic highpoint (32-34 m above
84 mean sea level) and has an average slope of approximately 2%. The near surface geology is
85 dominated by low permeability clay tills. The saturated hydraulic conductivity was measured

86 at 40 cm depth below terrain with a Guelph Permeameter at 20 random points on a 100x100m
 87 field located nearby with similar geological conditions. Results showed a saturated hydraulic
 88 conductivity with a geometric mean of $8.2 \cdot 10^{-7}$ m/s, a standard deviation of $1.8 \cdot 10^{-6}$ m/s, and
 89 no spatial correlation between the measuring points.



90
91 **Figure 2. The case study area.**

92 **The model**

93 The urban drainage model used in this study was a MIKE URBAN/MOUSE (Andersen et al.,
 94 2004) model set up by the companies HOFOR and Rambøll. The model covers a large area
 95 and it divides the area into several sub-catchments described by lumped parameters and
 96 connected to the sewer system at specified manholes. The surface runoff was calculated using
 97 the time-area method and the resulting hydrograph used as input to the hydrodynamic pipe
 98 flow model. Boundary conditions include dry weather flows in the local stream and water
 99 levels at lakes and at the estuary. The model includes pipe dimensions (slope, diameter,
 100 length, roughness) and connected surfaces (roofs, streets, backyards). Green areas were
 101 assumed to have a high infiltration capacity and therefore did not contribute to stormwater
 102 runoff.

103 The soakaway model integrated into MIKE URBAN (Roldin et al., 2012) was used to
 104 simulate the retention-detention units. The soakaway model is based on mass balance for the
 105 soakaway with infiltration rates (f) described as:

$$f = klw + k2h(l + w)$$

106 Where k is the soil hydraulic conductivity, l is length, w the width and h is the water level in
 107 the soakaway.

108 The retention-detention unit was modelled as a ‘basin’ in MIKE URBAN with infiltration
 109 rates determined from the soakaway model. The ‘basin’ was connected to the sewer system
 110 by 2 overflow pipes, one with a maximum rate (the lowest pipe) and the other without an
 111 outflow control.

112
113 **Sewer surcharge**

114 The impact of retention-detention units on sewer surcharge was modelled using single event
 115 simulation. A *Baseline scenario* and *Retention-detention* scenario was simulated. The input
 116 rainfall was a 4 hours duration Chicago Design Storm (CDS) (Keifer and Chu, 1957) event of
 117 10-years return period (5-minutes rainfall-intensity ≈ 90 mm/h) as determined using the
 118 Danish regional IDF curves (Madsen et al., 2009). The soakaway was designed for a 0.1-year

119 return period (19 mm of storage capacity) and the detention volume for a 10-year return
120 period (14 mm of storage capacity) (Table 1, Unit 1). The designed detention volume is a
121 function of the maximum flow rate through the ‘valve’ (see Figure 1) which was determined
122 as explained later in this section.

123

124 The *Baseline scenario* simulated the maximum water level in the drainage system. This was
125 then used to quantify the impervious area to be disconnected from the sewer in order to avoid
126 sewer surcharge. The area to be disconnected was determined by model trial and error and the
127 resulting area was connected to the retention-detention units.

128 The *Retention-detention scenario* simulated the water level in the drainage system in the
129 presence of the designed retention-detention units with several units modeled as a single
130 aggregated unit according to the method presented by Roldin et al. (2012). The error
131 introduced by upscaling was assumed to be comparable with the error calculated by Roldin et
132 al. (2012) that was on average 5%. Initial conditions for the retention-detention system were
133 chosen as shown in the section ‘Annual water balance and initial conditions’. The *Retention-*
134 *detention scenario* was an iterative process where the maximum controlled outflow rate from
135 the detention volume to the sewer (the flow through the ‘valve’ in Figure 1) was adjusted in
136 order to avoid sewer surcharge during the simulation. The maximum outflow rate obtained
137 was used to design the detention volume.

138 **Annual water balance and initial conditions**

139 The annual water balance and initial conditions of single retention-detention units were
140 modeled using 22-years of continuous simulations with a 1-minute time step and input
141 rainfall time series from Copenhagen.

142 Five different design return periods (Table 1, Unit 2-6) were considered for the soakaway.
143 The detention volume was not included in these simulations as it was found to have a small
144 impact on the annual water balance and initial conditions. This is because detention time
145 scale is about an hour, whereas the infiltration process from soakaways occurs over a period
146 of days. Moreover, the detention volume is exploited only few times a year (i.e.
147 approximately 10 times a year if the soakaway is designed for a 0.1-year return period).

Table 1. Retention-detention units

Section name in the paper	Unit	Retention volume (soakaway)			Detention volume			Total retention-detention volume
		Design return period*	Retention capacity	Soakaway volume / impervious area	Design return period	Detention capacity	Detention volume / impervious area	volume / impervious area
		[years]	[mm]	[m ³ / 100m ²]	[years]	[mm]	[m ³ / 100m ²]	[m ³ / 100m ²]
Sewer surcharge	1	0.1	19	1.9	10	14	1.4	3.3
Annual water balance and initial conditions	2	0.1	19	1.9		0	0	
	3	0.5	37	3.7		0	0	
	4	1	46	4.6		0	0	
	5	2	56	5.6		0	0	
	6	5	69	6.9		0	0	
Retention-detention volume combinations	7		0	0		33	3.3	3.3
	8		6.6	0.7		26.4	2.6	3.3
	9		13.2	1.3		19.8	2.0	3.3
	10		19.8	2.0		13.2	1.3	3.3
	11		26.4	2.6		6.6	0.7	3.3
	12		33	3.3		0	0	3.3

*soakaway cross section 1m x 1m.

149

150 Retention-detention volume combinations

151 The impact of different detention-retention volume combinations on peak runoff and annual
 152 water balance from single units was modeled with the same continuous simulations as shown
 153 above. Several volume combinations of retention-detention were modeled (see Table 1, Unit
 154 7-12). Results show peak reduction, defined as average reduction for the modeled single
 155 events with a return period between 1 and 10 years; and annual runoff reduction, defined as
 156 the average annual runoff reduction for the 22 year period.

157 RESULTS

158 Sewer surcharge

159 The *Baseline scenario* showed that the maximum water level observed in the sewer system
 160 during the single event simulation was above terrain (flooding). The area that must be
 161 disconnected in order to avoid flooding was found to be approximately 88%. The discharging
 162 capacity of the local pipe was reduced due to backwater from the downstream pipe, having a
 163 high water level due to water coming from outside of the case study area; this explains the
 164 high percentage of disconnection required.

165 Figure 3 shows the maximum water level observed in the sewer system for the *Retention-*
 166 *detention scenario*. The results show that sewer surcharge can be avoided by connecting 88%
 167 of the impervious area to the retention-detention unit. Similar results were obtained by Elliot
 168 et al. (2009) and Peters et al. (2007), who showed that stormwater infiltration devices reduce
 169 hydraulic peak loads. The maximum discharge capacity from the detention volume to the
 170 sewer system was found to be 25 l/s. The maximum discharge rate was used together with the
 171 intensity distribution of a 10-year return period rainfall event to find the required detention
 172 volume of 1.4 m³ for every 100 m².

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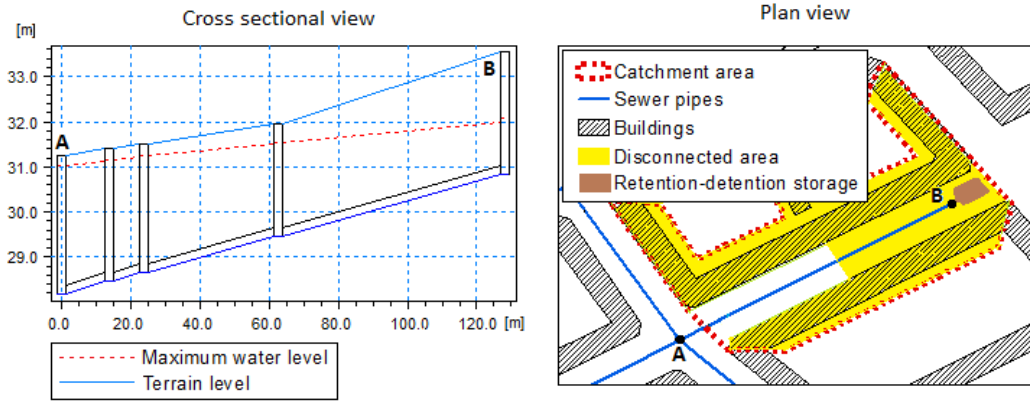


Figure 3. Maximum water level observed in the *Retention-detention scenario*.

175 Annual water balance and initial conditions

176 The simulated water content at the beginning of single rain events as a function of the
 177 soakaway design return period is shown in Figure 4 (right). Results show that the degree of
 178 filling is 5-94%. Moreover, the higher the soakaway design return period, the lower the water
 179 content at the beginning of rain events; this is because the bigger the storage volume the
 180 smaller the filling ratio for a fixed input water volume. Soakaways designed for a 0.1-year
 181 return period (the selected design) are on average 53% filled at the beginning of rain events.
 182 The peak runoff reduction capacity of soakaways is highly dependent on the available water
 183 storage at the beginning of the storm event, and it was shown that soakaways can be almost
 184 full at the beginning of an event. The detention storage coupled to the soakaway would most
 185 likely be empty at the beginning of rain events since it drains within an hour, making
 186 detention units a more robust solution for peak runoff reduction in this catchment.
 187 Figure 3 (left) shows the annual runoff infiltrated by soakaways. The volume of infiltrated
 188 water increases with the design return period and a soakaway designed for 0.1-years return
 189 period (the selected design) can infiltrate 68-87% of the annual volume. In comparison,
 190 Roldin et al. (2012) showed that soakaways could potentially reduce CSO volume by 68% in
 191 a modelled catchment. Freni et al. (2009) showed that an infiltration unit of $0.4 \text{ m}^3/100\text{m}^2$ in
 192 different soils could reduce 28-80% of the 6-year stormwater runoff.

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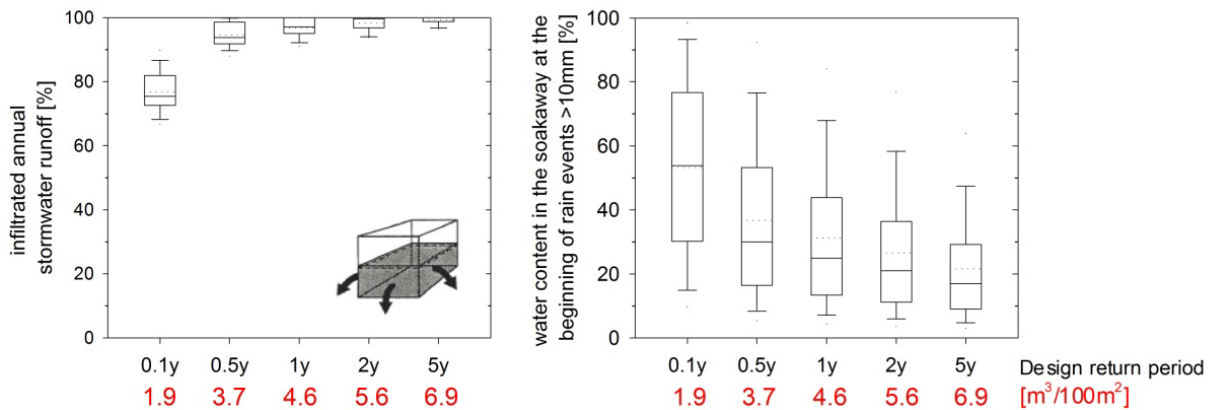
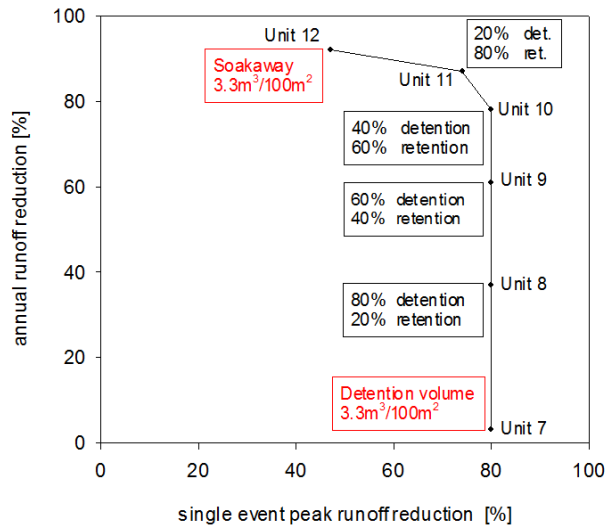


Figure 4. Continuous simulation results.

195 Retention-detention volume combinations

196 Figure 5 shows how the retention-detention volume combinations affect annual-runoff and
 197 single event peak-runoff reduction. Results show that a maximum of 80% peak reduction can
 198 be achieved; the volume combination '10' (Figure 5) is a better solution than '7', '8' and '9'
 199 since it scores higher in annual runoff reduction while having the same peak runoff
 200 reductions. This figure shows that the design could be based on multiple objectives and two

201 main conclusions can be drawn: (1) Allocating part of a soakaway volume to detention can
 202 significantly improve peak reduction with little impact on annual runoff reductions. A
 203 soakaway designed for a 5 year return period required 69 mm of storage capacity (Table 1)
 204 whereas a detention volume designed for a 10 year return period required 19 mm of storage
 205 capacity ('The retention-detention unit design' section), showing that detention requires
 206 significantly less storage compared to retention. (2) Allocating part of a detention volume to
 207 retention can improve annual runoff reduction with little impact on peak reduction.



208
 209 **Figure 5. Simulation results of retention-detention volume combinations.**

210

211 CONCLUSIONS

212 A retention-detention system was modelled. It was shown that soakaways require extremely
 213 large volumes if design events are to be handled without flooding, and that the peak reduction
 214 depends on the highly uncertain initial conditions. The initial conditions were determined by
 215 the degree of filling of the retention volume and were found to be 5-94% depending on the
 216 soakaway design. Coupling a detention unit to a soakaway was shown to significantly
 217 increase peak reduction. Retention-detention units were shown to be a more robust solution
 218 for peak runoff reduction because the detention volume is empty at the beginning of single
 219 events and has the capability of detaining peak flows.

220 A soakaway designed for a 0.1-year return period was shown to be 53% filled on average at
 221 the beginning of rain events making it insufficient to accommodate peak flow from a design
 222 event with a 10-year return period. Soakaways were shown to infiltrate more than 68% of the
 223 annual stormwater runoff if designed for a 0.1-year return period; which is a significant
 224 reduction in annual stormwater runoff volume to the sewer system.

225 The 3.3 m³/100m² retention-detention unit was shown to avoid sewer surcharge for a design
 226 event with a 10 year return period, reducing annual runoff by 68-87% and single events peak
 227 runoff by 80%.

228 This study showed that retention-detention units can reduce peak and annual runoff volumes
 229 and sewer surcharges and that adding a small detention unit to a retention unit can
 230 significantly improve peak stormwater runoff reduction. The results are specific to the Danish
 231 case study; however the modeling methodology can be applied to a broad range of
 232 conditions. The results illustrate the utility of retention-detention units, and the design
 233 presented can easily be modified to fit other climate and soil conditions.

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