Water sensitive urban design retrofits in Copenhagen – 40% to the sewer, 60% to the city

ABSTRACT
Water Sensitive Urban Design (WSUD) is emerging in Denmark. This interdisciplinary desk study investigated the options for WSUD retrofitting in a 15 km² combined sewer catchment area in Copenhagen. The study was developed in collaboration with the City of Copenhagen and its water utility, and involved researchers representing hydrogeology, sewer hydraulics, environmental chemistry/economics/engineering, landscape architecture and urban planning. The resulting catchment strategy suggests the implementation of five sub-strategies. First, disconnection is focused within sites that are relatively easy to disconnect, due to stormwater quality, soil conditions, stakeholder issues, and the provision of unbuilt sites. Second, stormwater runoff is infiltrated in areas with relatively deep groundwater levels at a ratio that doesn’t create a critical rise in the groundwater table to the surface. Third, neighbourhoods located near low-lying streams and public parks are disconnected from the sewer system and the sloping terrain is utilised to convey runoff. Fourth, the promotion of coherent blue and green wedges in the city is linked with WSUD retrofits and urban climate-proofing. Fifth, WSUD is implemented with delayed and regulated overflows to the sewer system. The results are partially adopted by the City of Copenhagen and currently under pilot testing.

Key words | combined sewer overflows, interdisciplinary research, stormwater, Sustainable Urban Drainage System, urban drainage

INTRODUCTION
Copenhagen and the neighbouring municipality of Hvidovre aim to develop an urban beach in the Kalveboderne estuary. In order to achieve bathing water quality in the estuary, the City of Copenhagen aims to reduce the number of Combined Sewer Overflows (CSOs) to the Harrestrup stream, which discharges into the Kalveboderne estuary, from approximately 200 overflows per year to approximately 20 per year (City of Copenhagen 2007). The objective of this study is to examine if and how Water Sensitive Urban Design (WSUD) retrofits can be implemented in Copenhagen to an extent that can meet this target.

WSUD is a supplement or alternative to sewer based urban drainage systems and covers a series of ecosystem service based approaches to urban stormwater management. WSUD technologies include, e.g. green roofs, rain gardens, bioswales, soakaways, wet basins, and dry basins.

A number of studies have analysed the role of WSUD to mitigate CSOs in existing cities (e.g. Villarreal et al. 2004; Semadeni-Davies et al. 2008). Others have reviewed the design of WSUD and its integration in the urban context (e.g. Mitchell 2006; Echols & Pennypacker 2008). However, none of the studies have been truly interdisciplinary in nature and only few studies, if any, have analysed the potentials and limitations for WSUD at catchment scale in existing urban settings. Assessing the potential of citywide
WSUD retrofits at a technological unit level (e.g. green roofs) is problematic as it might address the problem on too low a level. As argued by Rittel & Webber (1973: 165), ‘one should try to settle the problem on as high a level as possible’.

During 2007–2012, the Danish national strategic research project ‘Black, Blue and Green’ (2BG) explored options for WSUD retrofits in Danish cities in order to meet the challenges of combined sewer overflows and climate change. The 2BG project was developed as a collaboration between three Danish universities (Aarhus University, Technical University of Denmark, University of Copenhagen), four cities (Aarhus, Copenhagen, Greve and Odense; thereby including the local governments and water utilities of the three largest cities in Denmark), three major urban water consultancies (DHI, Grontmij, Alectia), two core professional associations (Danish Town Planning Institute, Danish Water and Wastewater Association) and the Danish Road Directorate. The key components of the 2BG project included the development of a WSUD training course for water and urban planning professionals (DANVA 2012), a series of national seminars, eight individual PhD projects, and two joint PhD case studies. The first joint case study was carried out in Odense in early 2008, with the purpose of establishing work relations across disciplines, and to get a better understanding of the organisational challenges linked with the introduction, planning and design of WSUD in existing cities. Findings were reported by Fryd et al. (2010). The second joint case study, which is outlined below, was implemented in Copenhagen during 2008–2009 and focused on options and limitations for WSUD retrofits in existing cities by employing research methods from multiple disciplines.

METHODS AND MATERIALS

From October 2008 to December 2009 the joint case study was carried out by eight PhD students enrolled on the 2BG project in close collaboration with their supervisors, and the end-users, City of Copenhagen (Centre for Parks and Nature), and the water utility, Copenhagen Energy Ltd. The research director for the 2BG project played a key role in setting up and facilitating the case study. The PhD students represented specific expertise with one PhD student from each of the following branches of research: urban drainage modelling, groundwater modelling, monitoring of water quality, treatment of stormwater runoff, water governance, environmental economics, landscape architecture, and urban planning. The study was developed in an iterative process with a series of ‘design loops’. It was structured during two workshops, one in October 2008 and one in March 2009, and five joint meetings between the researchers and end-users. Additional sub-studies were carried out independently or in smaller groups. Initial findings were presented at a national seminar in December 2009. Further detailing and analyses were carried out during 2010–2011.

The stormwater runoff eventually causing CSOs into the Harrestrup stream stems from the 15 km² catchment area shown in Figure 1. The catchment has approximately 100,000 inhabitants in four city districts, all served by the same combined sewer system. The catchment has sloping hills in the north, but is almost flat to the south. Two low-lying wetland areas, i.e. one along the Harrestrup stream and one along the Grondal stream, have resisted urban development and create a coherent Y-shaped system of public parks along the perimeter of the catchment. The geology is dominated by a low-permeable cap-layer of clayey till and only few deposits of filling materials. The catchment has shallow groundwater levels (<2 m) in the southern part close to the sea, and large distance to the groundwater (>2 m) in the northern part of the catchment located approximately 10 m above sea level and higher. Groundwater is extracted for drinking water supply purposes in the northern part of the catchment.

Copenhagen Energy Ltd. estimated that the goal of no more than 20 CSOs per year could be achieved by disconnecting 60% of the impervious surfaces from the sewer system, that is 60% of the total ‘reduced area’ contributing to stormwater runoff in the sewer catchment, and by managing the stormwater runoff from these surfaces by WSUD. This estimate was used as a guiding principle to get started. Existing planning documents and technical reports were consulted, e.g. regarding soil and groundwater conditions, and relevant geographic information system (GIS) data was provided by the end-users. In addition, international research literature was reviewed.

This paper complements two previously published articles deriving from the same case study (i.e. Backhaus & Fryd 2012; Roldin et al. 2012), by focusing on the catchment strategy as the specific outcome of the study and on the impact of the study on practice in Copenhagen. Further details about the design process were reported by Backhaus & Fryd (2012). Details about the set-up of models to support the study were reported by Jeppesen (2010) and Roldin et al. (2012).
RESULTS

To manage stormwater runoff from 60% of the impervious surfaces in the 15 km² catchment area an approach comprising five sub-strategies is suggested as illustrated in Figure 2.

Sub-strategy 1: WSUD at the easiest sites (i.e. the easiest 60% of the total impervious area)

At the outset it was assumed that WSUD retrofits are not equally easy at different sites and on different land use types (see Backhaus & Fryd 2012). Issues that influence land use complexity include, e.g.:

- the provision of unbuilt areas, in particular open green spaces and other permeable surfaces, relative to the amount of impervious surfaces within a given plot,
- the contaminant profile of the surface runoff from a given site,
- the number of property owners and other actors to involve in order to disconnect the area identified as necessary,
- the regulatory framework influencing site activities, and
- the potentially conflicting interests and concerns in relation to present and future land use(s).

Land use types were ranked to reflect their assumed suitability for WSUD retrofits. The hierarchy ranged from the relatively easy land use types such as existing public green spaces, schools, elderly homes, and social housing estates, to big-box warehouses, row houses, single family houses, perimeter blocks, residential roads, and sites under transformation, to the more complex land use types including densely built up areas, industrial estates, railway tracks, and major roads.

In addition to land use, the following conditions were expected to influence a site’s feasibility for WSUD retrofits:

- slope of the terrain,
- soil type,
distance to groundwater and the impact of infiltration on groundwater conditions,
whether the site is located upstream or downstream in the sewer catchment, and
risk of soil pollution resulting from past urban activities.

Sites on sloping ground are relatively easy (and cheap) to disconnect as stormwater runoff can be retained or directed though simple earth work changes. Soil types with a high hydraulic conductivity require relatively little area for infiltration compared with low permeable soil types. Low porosity soils with low water storage capacity cause a relatively large increase in the groundwater table as a result of increased infiltration compared to more porous soils. Disconnecting sites upstream in the sewer system has a positive impact on the entire downstream sewer system, whereas disconnections downstream do not influence upstream sewer capacity problems. Inappropriate uphill stormwater management can have a direct negative impact on downhill neighbours, whereas the opposite does not apply. Infiltration of stormwater through polluted soils can lead to groundwater contamination. In Denmark, groundwater is the primary source of drinking water, which has created strict policies on the control of groundwater quality and professional concern about the potential impact of urban stormwater infiltration on groundwater quality.

We selected sites for WSUD retrofits based on the above-mentioned hierarchy of land use types in combination with the list of specific conditions influencing a site’s suitability for WSUD retrofits. This was done in a stepwise, reflective and iterative process until 60% of the total impervious area was identified. The process also included the identification and shaping of sub-strategies 2–5. The change in focus from 100 to 60% of the impervious area is illustrated in Figure 2.1a.

All sites shown in Figure 2.1 must implement WSUD measures such as green roofs, rain gardens, rain tanks, or soakaways. The level of infiltration at each site, and the management of excess surface water leaving the site, is specified in sub-strategies 2–5 (i.e. Figures 2.2–2.5).

Sub-strategy 1a: Business-as-usual at the most difficult sites (i.e. the most difficult 40% of the total impervious area)

The most difficult sites continue discharging stormwater runoff directly to the combined sewer system, i.e.
business-as-usual. These sites (Figure 2.1a) include major roads, railways, and densely built up areas, as well as plots located in the flat, low-lying southern part of the catchment which is characterised by an existing shallow groundwater level. Combined, these sites comprise 40% of the total impervious area in the study catchment.

Sub-strategy 2: Stormwater infiltration

Groundwater supply interests apply to the northernmost part of the case study area. In addition, the distance to the groundwater level is relatively large at 3–4 m on average. This led to the promotion of stormwater infiltration in this part of the catchment. Simulations of the groundwater response to different infiltration scenarios suggested that only between zero and 30% of the impervious area could be connected to infiltration measures (i.e. soakaways) without resulting in a critical rise in the groundwater table to reach sewer connected drains located 1 m below the surface, thus, eventually increasing groundwater intrusion into the sewer system and groundwater to be treated at the centralised wastewater treatment plant. See Jeppesen (2010) for details. This infiltration ratio is illustrated in Figure 2.2 by showing 10% of the buildings located between 16 and 19 m above sea level (m.a.s.l.), 20% of the buildings located between 19 and 22 m.a.s.l., and 30% of the buildings located higher than 22 m.a.s.l.

Connecting 0–30% of the impervious area to soakaways in the northernmost sewer catchment area is estimated to reduce the volume of annual CSOs by approximately 24%, and the number of CSOs from 5.2 to 4.4 per year per CSO structure (Roldin et al. 2012). Hence, by implementing soakaways as the only WSUD option, Copenhagen will not be able to meet the goal of reducing the CSO frequency to one per overflow structure per year. In addition, the implementation of soakaways is complicated by the fact that they will need to be implemented on private properties. Construction cost in addition to transactions cost provide a considerable obstacle for private property owners. Furthermore small scale facilities, which private property owners would implement, are less cost-effective than larger facilities making small scale less attractive from a planning perspective (Zhou et al. 2013). At the same time the present regulation system in Denmark provides an inefficient incentive scheme which makes households reluctant to implement soakaways and similar facilities on private properties (ibid.).

The residual volume, i.e. runoff from 70 to 100% of the impervious area in the northern part of the catchment, should be managed by means of non-infiltration measures as described in sub-strategy 4 and 5, see below. The implementation of infiltration and non-infiltration measures is illustrated in Figure 3.1.

Sub-strategy 3: Overflow to parks and streams

Neighbourhoods located near and immediately uphill of low-lying streams and public parks are disconnected from the sewer system (Figure 2.3). The sloping terrain along streets is utilised to convey stormwater runoff from allotments and local roads to the public green areas (Figure 3.2). Runoff is treated prior to discharge or seepage to the stream, either by means of engineered soil (Ingvertsen et al. 2012) or Dual Porosity Filtration (Jensen et al. 2011a). Storage volume to facilitate treatment and delayed discharge is provided upstream of the stormwater treatment facility.

Sub-strategy 4: Overflow to blue and green wedges

The implementation of WSUD is actively linked with the promotion of coherent urban blue and green wedges in
Copenhagen. Green corridors connect existing larger parks and expand the city’s network of walkways, running paths and bicycle lanes. Blue connections (shown as thin lines in Figure 2.4a) reflect emergency surface runoff routes during high intensity rain events. The blue connections convey excess stormwater runoff from uphill plots (such as single family houses and social housing estates) along streets to downhill blue and green wedges. The proposed combined blue and green wedges (shown as bold lines in Figure 2.4a) are strategically located where the blue connections and green corridors can be united. The blue and green wedges utilise the local topography by creating a system of low-lying floodways while improving ecological connectivity in the city. The blue and green wedges fully or partly replace existing streets which are relatively wide compared with the traffic load and thus they don’t radically compromise the flow of motorised traffic (Figure 3.3). This creates a network of artificial tributaries in the city that convey, retain and treat stormwater runoff, discharge excess water into natural waterways, and help prepare Copenhagen for a changing climate with more intensive rain events and longer periods of drought.

The value of green spaces depends partly on size and type of space. Flood systems in green spaces can provide a considerable benefit to surrounding neighbourhoods in the form of increased access to recreational services. However, this heavily depends on the design of the flood system. A lake located in a park or natural area which is able to handle an additional influx of stormwater will be perceived as a recreational benefit while an occasionally flooded green space will be perceived as a disamenity (Panduro & Veie submitted).

**Sub-strategy 5: Overflow to sewers**

The remaining sites have WSUD with delayed and regulated discharge to the sewer system (Figure 2.5). Non-infiltration measures such as green roofs, rain tanks and wet basins are promoted. WSUD based on surface infiltration and retention, such as rain gardens, bioswales, and infiltration lawns, are equipped with drains into the sewer system.

**Impact of the case study on WSUD in Copenhagen**

The case study has directly impacted policy in the City of Copenhagen. In the Copenhagen Climate Adaptation Plan (City of Copenhagen 2011), the primary adaptation strategy is the disconnection of impervious surfaces from the sewer system and stormwater management through retrofitted WSUD measures. This is prioritised above sewer enlargements. The case study has contributed to formulating specific sub-studies for the City of Copenhagen to proceed with. Follow-up research and development projects have been financed by the City of Copenhagen and Copenhagen Energy Ltd. Following sub-strategy 3, a study of the specific options for collection and treatment of stormwater runoff from local roads along low-lying park areas has been concluded (Jensen et al. 2011b). Full-scale pilot projects on the treatment of road runoff using engineered soils (Ingvertsen et al. 2012) and Dual Porosity Filtration (Jensen et al. 2011a) are currently being implemented at two test sites along the Harrestrup stream within the framework of the national Danish innovation consortium, Cities in Urban Water Balance (www.byerivandbalance.dk). In addition, researchers from the study have been commissioned to participate in the development of a flood mitigation strategy for Copenhagen which elaborates on elements in the sewer catchment strategy and other findings from the Copenhagen case study. Similarly, the case study has initiated test sites for establishing water balances for green roofs, as well as the development of guidelines for the management of stormwater runoff in accordance with the EU Water Framework Directive, both within the strategic partnership, Water in Urban Areas (www.vandibyer.dk).

**DISCUSSION**

The case study indicates that there is no one-size-fits-all approach to WSUD retrofits. The five sub-strategies provide specific solutions for each site and are developed by balancing land use type, site conditions, and urban development goals within the catchment area.

In addition, the study shows that the need for interdisciplinary collaboration increases when WSUD is scaled up from plot scale to catchment scale. One example is the treatment of stormwater runoff from local streets which was assessed and found necessary by the environmental chemists in the research team on top of an initial concept developed by the team’s landscape architect and urban planner. Another example is the impact of large scale stormwater infiltration on groundwater conditions and CSOs. This assessment required close collaboration between a groundwater modeller, an urban drainage modeller, and an urban planner. For details, see Roldin et al. (2012).

The described study is based on desktop analyses and includes no field measurements or test sites, and as such, there is still a long way to go before the concepts and
estimates can be qualified and tested. As an example, the balancing of plot, district, and catchment level WSUD measures has not been thoroughly investigated, e.g. in terms of the costs and benefits of alternative design options. It remains a conceptual design idea, though more nuances to the study can be extracted from Backhaus & Fryd (2012), Roldin et al. (2012) and Zhou et al. (2013).

There is a risk that the strategy is identified as a one-off design. It is not to be regarded as a fixed blueprint. Rather, the strategy serves to guide initial actions that can be assessed and refined over time. On the one hand, the proposed strategy can be criticised for being overly optimistic about the potential of blue connections in the city (sub-strategy 4), i.e. the potential of conveying stormwater on and along existing streets in the city despite the present lack of knowledge about the pros and cons of this option. On the other hand, the strategy might be conservative in estimating the impact of infiltration on groundwater levels (sub-strategy 2). This is linked with much uncertainty about local soil condition, evapotranspiration processes in the unsaturated zone, and the lateral groundwater flow and seepage into streams and the sea.

Roldin et al. (2012) assessed the impact of soakaway retrofits on CSOs in the north-western part of the catchment and developed a method to examine the impact of WSUD retrofits on CSOs. Still, the impact of the proposed WSUD retrofit strategy on the number of CSOs for the catchment as a whole has not been examined. The case study responds to the expected need for disconnection, but does not fully conclude on the impact of WSUD retrofits on CSOs to the Harrestrup stream. The design and modelling tools necessary for such an integrated assessment were initially developed during the case study and have been refined during the course of the eight individual 3-year PhD studies developed within the 2BG framework. Hence, the tools are available for follow-up studies. It is expected that the ongoing research in Copenhagen will further appropriate the initial assumptions and findings.

CONCLUSIONS

The interdisciplinary case study of a 15 km² sewer catchment in Copenhagen explored options for managing stormwater runoff from 60% of the impervious area by means of WSUD retrofits. The study suggested five sub-strategies related to land use type, site conditions, and potential synergy with strategic urban development. It generated concrete project tasks, e.g. concerning collection, treatment and discharge of road runoff, which are currently being adopted and tested at full scale by the City of Copenhagen. The effectiveness of the proposed WSUD retrofit strategy to mitigate CSOs into the Harrestrup stream from Copenhagen is not yet identified, but it is expected that it will be appropriated through pilot projects over the coming years.

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