ABSTRACT
WSUD is emerging in Denmark. An integrated multidisciplinary case study has investigated the options for WSUD retrofitting in a 15 km² combined sewer catchment area in Copenhagen, Denmark, with the aim of reducing combined sewer overflows. The study was developed in collaboration with the City of Copenhagen and its water utility board, and involved researchers representing hydrogeology, sewer hydraulics, environmental chemistry, economics, engineering, urban planning and landscape architecture. The resulting multi-level catchment strategy, with a target of disconnecting 60% of the impervious area, suggests the implementation of four sub-strategies. First, disconnection is focused within sites that are relatively easy to disconnect, due to water quality, soil conditions, and the provision of open space. Secondly, up to 30% of the annual stormwater run-off is infiltrated in areas with relatively deep groundwater levels. Third, neighbourhoods located near low-lying wetland areas are disconnected and the sloping terrain is utilised for the conveyance of stormwater runoff. Fourth, the promotion of coherent urban green infrastructures is linked with WSUD transformations, urban greening and urban climate-proofing. In combination, these make the goal of 60% disconnection achievable. The study has generated four scientific papers so far, as well as concrete outputs which are partially adopted and currently under full-scale testing by the City of Copenhagen.

KEYWORDS
Combined sewer overflows, sustainable urban drainage systems, retrofit, interdisciplinary research

INTRODUCTION
Cities throughout Denmark have experienced a series of stormwater flash floods during the past 5-10 years. This, in combination with the on-going climate change debate and the intensive media coverage, has dramatically raised the general public’s awareness of stormwater and flood risk management in urban areas in Denmark. Furthermore, as an EU member state, Denmark must improve the chemical and ecological conditions in urban recipient areas (EU WFD, 2000). In addition, several cities aim to develop urban beaches and harbour bathing areas to enhance urban liveability. In order to reach and maintain bathing water quality, a reduction in combined sewer overflows (CSOs) is often needed (e.g. City of Copenhagen, 2007).
Since 2007, the Danish national strategic research project “Black, Blue and Green” (2BG) has explored options for WSUD based transformations of Danish cities in order to meet these challenges. The 2BG project was developed as a collaboration between three 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 professional associations (Danish Town Planning Institute, Danish Water and Wastewater Association) and the Danish Road Directorate. The key components of the 2BG project include the development of a WSUD training course for water and urban planning professionals, 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 planning of WSUD. Findings were reported by Fryd et al. (2010). The second case study, which is outlined below, was implemented in Copenhagen during 2009. It focused on the technical challenges and limitations for WSUD retrofits and emphasised in-depth research within and between research disciplines.

Copenhagen and the neighbouring municipality of Hvidovre aim to develop an urban beach in the Kalveboderne estuary. The Harrestrup stream, which has a 70 km² catchment area and drains nine urbanised municipalities, discharges into the Kalveboderne estuary. At present, the stream receives around 200 CSOs per year from the city of Copenhagen alone. The total number is higher if all municipalities are included. In order to achieve bathing water quality in the Kalveboderne estuary, the City of Copenhagen aims to reduce the number of CSOs to approximately 20 per year, which is an average of one overflow per overflow structure, per year (City of Copenhagen, 2007).

This study has two objectives:
1) To examine if and how the number of CSOs into the Harrestrup stream from Copenhagen can be reduced to the desired goal of 20 per year, by means of WSUD retrofits in existing urban areas.
2) To explore the effectiveness of a joint case study as a method to facilitate multidisciplinary research.

METHODS
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, the City of Copenhagen (Centre for Parks and Nature), and the water utility, Copenhagen Energy Ltd. The PhD students represented specific expertise on urban drainage modelling, groundwater modelling, monitoring of water quality and treatment of stormwater runoff, stakeholders’ perspectives, spatial environmental economics, landscape architecture and urban design. 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 and reported by Fryd et al. (2009). Further detailing and analyses have been carried out afterwards. Below, the number of peer-reviewed papers linked to this specific case study is used as an indicator of the effectiveness of a joint case study as a method to facilitate multidisciplinary research.

The stormwater runoff eventually causing CSOs into the Harrestrup stream stems from the catchment area shown in Figure 1. Copenhagen Energy estimated that the goal of no more than 20 CSOs per year could be achieved by disconnecting 60% of the impervious surfaces in the sewer.
catchment area. As a start, planning documents and technical reports were consulted (e.g. regarding soil and groundwater conditions) and relevant GIS data was provided by the City of Copenhagen and Copenhagen Energy Ltd. Details about the case study design and the set-up of models are reported by Backhaus and Fryd (in press), Jeppesen et al. (forthcoming), and Roldin et al. (submitted). In addition, international research literature was reviewed.

**Figure 1.** The case study area (red outline) in Copenhagen, Denmark, covers 15 km² and has approximately 100 000 inhabitants in four city districts, all served by the same combined sewer system. The catchment causes approximately 200 combined sewer overflows per year into the Harrestrup stream, which discharges into the Kalveboderne Estuary.

**RESULTS AND DISCUSSION**
As an outcome of the case study process, an integrated catchment strategy suggests that 60% of the impervious area must be fully or partially disconnected from the sewer system and managed by means of WSUD. Four sub-strategies are utilised, see Figure 2.
Figure 2. Multi-level strategy for WSUD retrofits in Western Copenhagen.

**Direct or controlled discharge to sewers.** Due to shallow groundwater depths (Jeppesen et al., forthcoming) most impervious surfaces in the southern part of the case study area continue to discharge stormwater runoff into the combined sewer system (i.e. “business-as-usual”). It is suggested, however, that schools, multi-storey apartment blocks and other land use types with simple stakeholder conditions and good provision of green space are disconnected to promote volume reduction and delay. SUDS based on surface infiltration and retention, e.g. rain gardens, swales, and infiltration lawns, equipped with drains into the sewer system are recommended for such areas. Green roofs are recommended too, to reduce the risk of rising groundwater levels in response to climate change.

**Stormwater infiltration zone.** In the northernmost areas it is possible to infiltrate up to 30% of the annual precipitation from all impervious surfaces. The residual volume should be managed by means of evapotranspiration, retention, local water supply, reduced discharge to sewers, or be conveyed in a separate stormwater system onto or near to the terrain surface, see Figure 3a. The implementation of soakaways in the northernmost sewer catchment area is estimated to reduce the volume of CSOs by approximately 20%, and the number of CSOs from seven to five per year per CSO structure (Roldin et al., submitted). Hence, by implementing soakaways as the only WSUD option, Copenhagen cannot meet the goal of reducing the CSO frequency to one per overflow structure per year.

**Discharge or seepage to streams.** Neighbourhoods located near low-lying wetlands and streams are disconnected from the sewer system. The sloping terrain along the streets is utilised to convey stormwater run-off from allotments and local roads to the wetland areas, see Figure 3b. Runoff is treated prior to discharge or infiltration/seepage, either by means of engineered soils (Ingvertsen et
al., submitted) or Dual Porosity Filtration (Jensen et al., 2011a). Storage volume is provided upstream of the stormwater treatment facility.

**Urban blue and green corridors.** The promotion of coherent urban green infrastructures is linked with WSUD and urban climate proofing to manage high intensity rain events. Green corridors fully or partly replace existing streets along strategic routes, see Figure 3c. Besides serving the purposes of stormwater retention and conveyance on a larger urban scale, the green corridors are integrated with cycle, running and walking paths and ecological corridors through the city. During extreme rain events, the green corridors work as flood ways.

![Figure 3.](image)

In combination, the four sub-strategies are expected to reach the goal of disconnecting 60% of the impervious surfaces in the 15 km² sewer catchment area. Despite the sub-study in the north-western part of the catchment (Roldin et al., submitted), no integrated modelling scenario was employed to assess the impact of the multi-level strategy on the number of CSOs for the catchment as a whole. The study responded to the expected need for disconnection, but did 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 and expanded during the course of the eight individual 3-year PhD studies. Hence, the tools are available for follow-up studies.

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. However, a range of follow-up projects are currently being conducted (see below).

Four of the 24 international peer-reviewed papers currently arising from the 2BG project are directly linked to the integrated study in Copenhagen (2BG, 2011). The problem-oriented and site-specific case study proved relevant as a method to integrate urban planning, landscape architecture, hydrogeology and urban drainage modelling at sewer catchment scale; to be specific:

Jeppesen et al. (forthcoming) developed an integrated urban water model with five WSUD elements (i.e. green roofs, soakaways, grass infiltration areas, swale-trench systems, and water tanks) and modelled the groundwater response. They concluded that a maximum of 30% of the annual precipitation can be infiltrated without causing a critical rise in the groundwater table to the terrain surface.

Roldin et al. (submitted) builds on the findings of Jeppesen et al. (forthcoming) and estimates the impact of soakaways on CSOs in the north-western part of the sewer catchment. Given the poor
infiltration potential, the number of annual CSOs is not reduced, whereas the average CSO volume is expected to be reduced by approximately 10%.

Backhaus and Fryd (*in press*) analyse the case study as a research by design process. They define breakthroughs and set-backs which should be prepared for in future WSUD planning and design projects.

Correspondingly, Backhaus *et al.* (*in press*) implement a sub-study where practicing landscape architects develop ideas and solutions for a specific site within the case study sewer catchment area. They identify site-specific and generic challenges in the design process for WSUD.

This multidisciplinary approach helped to provide insights and knowledge exchange across disciplinary fields. Though this does not necessarily lead to specific research papers (the indicator used above), the obtained knowledge is seen as an asset to all the urban water professionals involved in the study, who were all striving for a more holistic/realistic perspective on the options and limitations for WSUD.

The case study did not lead to papers about stormwater monitoring and treatment schemes specific to the given catchment area. However, the implicit knowledge is being applied and utilised as indicated below.

**Impact of the case study on WSUD in Copenhagen**
The case study has directly impacted policy in the City of Copenhagen. In the 2011 Copenhagen Climate Change Adaptation Plan (City of Copenhagen, 2011), disconnections and stormwater management in the urban landscape are the primary adaptation strategy, prioritized above sewer enlargements. Indirectly, the case study has inspired a number of additional municipalities in Denmark to explore the adoption of WSUD. This trend can be observed in the rapidly growing database of Danish WSUD methods and projects [www.laridanmark.dk](http://www.laridanmark.dk).

Furthermore, 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. A study of the specific options for collection and treatment of stormwater runoff from local roads along low-lying wetlands has been concluded (Jensen *et al.*, 2011b). Within the framework of the national innovation consortium, Cities in Urban Water Balance ([www.byerivandbalance.dk](http://www.byerivandbalance.dk)), full-scale pilot projects on the treatment of road runoff using engineered soils (Ingvertsen *et al.*, *submitted*) and Dual Porosity Filtration (Jensen *et al.*, 2011a), are currently being implemented at two test sites along the Harrestrup stream.

**CONCLUSIONS**
The case study successfully linked disciplines in a joint effort to envision WSUD for Copenhagen. The case study approach seemed particularly effective as a tool to link urban planning, landscape architecture, hydrogeology and urban drainage on a larger scale for urban sewer catchments; but was in fact valuable to all actors. The study 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.
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