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Modelling the impact of soakaway retrofits on combined sewage overflows in a 3 km^2 urban catchment in Copenhagen, Denmark

Maria Roldin [a,*], Ole Fryd [b], Jan Jeppesen [c], Ole Mark [d], Philip J. Binning [a], Peter Steen Mikkelsen [a], Marina Bergen Jensen [b]

[a] Technical University of Denmark, Dept. of Environmental Engineering (DTU Environment), 2800 Kgs Lyngby, Denmark
[b] University of Copenhagen, Rolighedsvej 23, 1958 Frederiksberg, Denmark
[c] ALECTIA A/S, Skanderborgvej 190, 8260 Viby J, Denmark
[d] DHI, Agern Allé 5, 2970 Hørsholm, Denmark

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SUMMARY

Stormwater infiltration measures such as soakaways are expected to be part of future urban drainage systems. However, few studies exist on the effect of extensive stormwater infiltration through soakaways on the overall urban water system, including sewers and groundwater, at city catchment scale. In particular such estimates have not been made in real urban settings with multiple physical and structural constraints. This paper presents a methodology for conducting such an analysis, and provides quantitative estimates of the effects on the urban water flows. Using an interdisciplinary, three-step approach that employed GIS analyses and physically distributed, dynamic pipe flow modelling in an iterative manner, this study estimates the impact of infiltration on combined sewage overflows (CSOs) in a 3 km^2 urban catchment in Copenhagen. The first step was the creation of a baseline scenario. The second step led to a potential infiltration scenario where 65% of the total impervious area was connected to soakaways, and resulted in an estimated reduction in annual sewage overflow volume of 68%. This scenario was then further developed in the third step by adding groundwater constraints, which formed a more realistic scenario where only 8% of the impervious area was connected to soakaways and the reduction in CSO volume was 24%. The potential and realistic scenarios were modelled both with hydraulic coupling between soakaway and sewer, and as fully disconnected. Results show that infiltration is constrained mainly by the quality of the stormwater runoff from roads and limited land availability in the potential infiltration scenario, and by low-permeable soils and a problematically high groundwater level in the realistic infiltration scenario. The hydraulically coupled model gives higher CSO volume than the fully disconnected model for the potential infiltration scenario, whereas no difference is seen between these two models in the realistic infiltration scenario. The effect of infiltration on combined sewer overflows is thus expected to be limited in the case study area. General conclusions are that groundwater constraints are important to consider when evaluating the potential of infiltration-based stormwater management, and that it is important to include the hydraulic coupling between soakaways and sewers in models if soakaways are expected to give overflow to the sewers.

1. Introduction

The capacity and service level provided by existing sewer systems is challenged by an increase of impervious surfaces in urban areas (e.g., Pauleit et al., 2005), more intensive rain events resulting from climate change (e.g., Larsen et al., 2009), and increasing focus on the ecological condition of receiving water bodies (e.g., EU WFD, 2000). Water Sensitive Urban Design (WSUD) elements are commonly used in many countries today (e.g. Revitt et al., 2003), and are expected to be an even more important part of the future urban drainage regime and a key to lessen the stormwater load on existing sewer systems (e.g. Chocat et al., 2007; Dietz and Clausen, 2005; Ellis, 2000; Göbel et al., 2004; Mikkelsen et al., 1996; Villarreal et al., 2004).

In many countries, one of the most common WSUD retrofit options for stormwater management on private allotments and alongside roads is underground soakaways, such as underground seepage pits and linear subsurface infiltration trenches (Rauch et al., 2005; Revitt et al., 2003). Soakaways do not compromise other uses on the surface which is a particular advantage in densely populated areas.

* Corresponding author. Tel.: +45 4525 1690.
E-mail address: mkbe@env.dtu.dk (M. Roldin).

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1.1. Documented effects of soakaways on urban water flows by modelling and measurements

Measurements have been made to identify the efficiency of standalone soakaways (e.g. Bergman et al., 2011; Lindsey et al., 1992; Warnaars et al., 1999). Modelling studies have been carried out on theoretical catchments (e.g. Petersen et al., 1994) and on real catchments at allotment and neighbourhood scale (e.g. Markussen et al., 2004; Xiao et al., 2007) and at city scale (Peters et al., 2007) to assess effects on sewer flows. These studies found that infiltration of stormwater can have a substantial effect on the runoff and combined sewer overflows, but the efficiency is highly sensitive to the physical properties of the soil. Markussen et al. (2004) also evaluated the effects on groundwater levels and concluded that the infiltrated stormwater will contribute to increased groundwater recharge, but also to sewer flows through increased flow from connected drainage pipes. Moreover, the impact of infiltration on groundwater has been simulated at sewer catchment level in two studies by Göbel et al. (2004, 2007). The latter employed various analytical and numerical simulation models in an area-differentiated water balance program to conclude that stormwater infiltration can be controlled to fit local groundwater conditions and promote near-natural groundwater conditions. Holman-Dodds et al. (2003) did an integrated study of the impact of stormwater infiltration in an urban watershed, and found that infiltration based stormwater measures were most efficient in terms of runoff reduction for small and frequent rainfall events. A recent study by Maimone et al. (2011) investigated the effects of extensive implementation of stormwater infiltration measures on groundwater levels in Philadelphia, US, both on local and city-wide scale and concluded that groundwater elevation is an important factor to consider in order to assess the potential impact on basement flooding and on local surface waters. None of the city-scale groundwater studies modelled the effect of soakaways on sewer flows. However, both Maimone et al. (2011) and Markussen et al. (2004) concluded that a large part of the infiltrated stormwater will end up in the sewer system through drainage pipes, but at a slower rate due to the detention effect, which is less likely to lead to surcharges and combined sewer overflows. Furthermore, infiltration of stormwater can increase sewage flows due to remobilisation of soil water (e.g. Antia, 2009).

The modelling of effects of soakaways on sewer flows differs from detention basin modelling (which has been described in numerous publications in the past decades) in several ways. Soakaways are generally small-scale structures that are implemented locally in a garden or backyard, whereas detention basins typically are central, large-scale stormwater facilities. Furthermore, soakaways are situated below ground, and are designed to infiltrate the water that enters. They may have an overflow structure leading excess water (beyond the designed soakaway capacity) to the sewer system when the soakaway is full, to prevent valuable assets from being flooded during extreme rainfall events. Detention basins are usually above ground, and the discharge is continuously led to a natural streamflow or back to the sewer system via a small outlet at the bottom of the basin. These differences are important to consider when assessing the effects of soakaways on sewer flows, and highlights the need for a modelling approach adapted for soakaways. Roldin et al. (2012) developed a model to facilitate detailed simulation of the hydrodynamic impact of soakaways on sewer systems. This model allows to quantify the infiltration of stormwater and to model the potential overflow of stormwater from the soakaway back to the sewer system, which is disregarded in many other similar studies (e.g. Semadeni-Davies et al., 2008). The hydraulically coupled model can also be used to estimate the risk of backwater effects from sewage system to soakaways, which is particularly important for soakaways located in a combined sewage area. The soakaway model includes an upscaling feature to aggregate several soakaways which makes it possible to quantify the effects of soakaways on the urban drainage system without modelling each structure individually (Roldin et al., 2012). Issues related to the complexity of upscaling soakaways in groundwater models, such as interaction between multiple soakaways and interfering groundwater mounds, have been covered by e.g. Maimone et al. (2011) and Antia (2008) but are not included in the module by Roldin et al. (2012) since it focuses on sewer interaction.

The implementation of soakaways in a city area is constrained by land limitations and existing built environments, existing underground infrastructures, soil pollution, groundwater levels, local drinking water assets, and the quality of the stormwater runoff (Göbel et al., 2008; Mikkelsen et al., 1994; Pitt et al., 1999; Revitt et al., 2003). To make an analysis that covers these aspects, an interdisciplinary approach linking (at least) urban water engineering, geosciences, and urban planning is required (Fryd et al., 2010; Göbel et al., 2004; Markussen et al., 2004; Rauch et al., 2005). To date, there are very few, if any, documented studies of the effects of extensive stormwater infiltration through soakaways on the overall urban water system, including sewers and groundwater, at city catchment scale. The results from such a case study are of course site specific. However, the methods, required datasets and assumptions are general and can be used by others to investigate the viability of soakaways in other geographical, geological, and climatic contexts.

1.2. Problem definition, aim and delineation of this study

The city of Copenhagen has expressed an ambition to achieve bathing water quality in all the inner city harbour and coastal waters. To meet this goal, the municipality estimates that the existing frequent overflows from the combined sewer system (CSOs) to the local streams must be reduced to maximum 1 overflow event per year and structure (City of Copenhagen, 2007). The recently adopted climate change adaptation plan for Copenhagen emphasises the importance of local and small-scale stormwater solutions to reduce current and future problems related to stormwater management (City of Copenhagen, 2011), and soakaways and similar infiltration structures are widely promoted by the municipality, e.g. through economic incentives allowing partial reimbursement of the sewage connection fee if private land owners decide to disconnect stormwater from the combined sewer system and manage water locally within their own allotment (Copenhagen Energy, 2012). There are, however, several constraints that make extensive infiltration of stormwater in the Copenhagen area problematic; low permeability soils, high groundwater tables, polluted soils and drinking water assets are frequently found (City of Copenhagen, 2009). In addition to this, many areas are densely built and the available space for stormwater management is limited.

To answer the question whether infiltration through soakaways is (part of) a possible solution for reducing CSOs in this area, there is a need for an interdisciplinary analysis able to deal with the complexity of the system and the multiple constraints involved. The novelty of this study lies within a three-step approach where the first step defines the baseline scenario and the second step outlines the potential of infiltration of stormwater based on a detailed level of town planning in combination with the use of a physically distributed coupled soakaway-urban drainage model at city catchment scale. The potential infiltration scenario is then in a third step combined with the results of a groundwater modelling study to form a more realistic infiltration scenario. The entire study is characterised by an iterative, cross-disciplinary workflow.