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PhD Thesis
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The synopsis part of this thesis is available as a pdf-file for download from the DTU research database ORBIT: http://www.orbit.dtu.dk

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Preface

This PhD project, entitled "Modelling the impact of Water Sensitive Urban Design technologies on the urban water cycle", was carried out at the Department of Environmental Engineering (Technical University of Denmark) in the period 2012-2015. The project was supervised by Prof. Philip J. Binning (DTU Environment), Dr. Ole Mark (DHI), Prof. Peter Steen Mikkelsen (DTU Environment) and Prof. Karsten Arnbjerg-Nielsen (DTU Environment). The PhD project was funded by the Innovation Fund Denmark through the innovation consortium BIV (Byer I Vandbalance - Cities in water balance).

This PhD thesis consists of a synopsis and 5 papers submitted to scientific journals. The papers in the synopsis are referred to by roman numbers:

I. **Locatelli, L.**, Mark, O., Mikkelsen, P.S., Arnbjerg-Nielsen, K., Jensen, M. B., Binning, P.J, 2014. Modelling of green roof hydrological performance for urban drainage applications. Journal of Hydrology, 519, Part D: 3237-3248.

II. **Locatelli, L.**, Gabriel, S., Mark, O., Mikkelsen P.S., Arnbjerg-Nielsen, K., Taylor, H., Bockhorn, B., Larsen, H., Kjølby, M.J., Blicher A.S., Binning, P.J., 2015. Modelling the impact of retention-detention units on sewer surcharge and peak and annual runoff reduction. Water Science and Technology, 71(6), 898-903.

III. Roldin, M., **Locatelli, L.**, Mark, O., Mikkelsen, P.S., Binning, P.J., 2013. A simplified model of soakaway infiltration interaction with a shallow groundwater table. Journal of Hydrology, 497, 165–175.

IV. **Locatelli, L.**, Mark, O., Mikkelsen, P.S., Arnbjerg-Nielsen, K., Wong, T., Binning, P.J., 2015. Determining the extent of groundwater interference on the performance of infiltration trenches. Journal of Hydrology, 529, Part 3: 1360-1372.

V. **Locatelli, L.**, Mark, O., Mikkelsen, P.S., Arnbjerg-Nielsen, K., Roldin, M., Deletic, A., Binning, P.J. Groundwater flooding and hydrologic impacts of catchment-wide stormwater infiltration. Manuscript.

In this online version of the thesis, paper **I-V** are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from DTU Environment, Technical University of Denmark, Miljoevej, Building 113, 2800 Kgs. Lyngby, Denmark, info@env.dtu.dk.

The following articles and reports were also prepared during the project:

Locatelli, L., Mark, O., Mikkelsen, P.S., Arnbjerg-Nielsen, K., Kleinlercher, B., Roldin, M., Binning, P.J., 2013. A simple rainfall–runoff model for the single and long term hydrological performance of green roofs, Novatech 2013. Lyone, France.

Bockhorn, B., Klint, K.E.S., **Locatelli, L.**, Park, Y.J., Binning, J.P., Sudicky, E., Jensen, M.B, 2015. Factors affecting the hydraulic performance of infiltration based SUDS in clay. Urban Water Journal, DOI:10.1080/1573062X.2015.1076860.

Locatelli, L., Bockhorn, B., Binning, P.J., Klint, K.E.S., Mark, O., Mikkelsen, P.S., Olesen, H, Bischoff, N., 2014. Report. Stormwater infiltration in Beder. Byer I Vandbalance. DTU Environment.

Locatelli, L., Binning, P.J., 2012. Report. Injection wells for stormwater infiltration at Beder. Byer I Vandbalance. DTU Environment.

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Summary

Alternative stormwater management approaches for urban developments, also called Water Sensitive Urban Design (WSUD), are increasingly being adopted with the aims of providing flood control, flow management, water quality improvements and opportunities to harvest stormwater for non-potable uses. WSUD structures (WSUDs) are typically small, decentralized systems for managing stormwater runoff near the source. These systems interact with the urban hydrological cycle, modifying the evapotranspiration, runoff and groundwater recharge fluxes. It is challenging to quantify these hydrological changes because of the cost and complexity of modelling multiple WSUD systems in larger scale urban catchments. For this reason, new modelling tools are needed. These tools must be simple enough to be computationally efficient, while still describing the observed hydrological responses of urban catchments. The models must be able to simulate both the response of single WSUDs and many coupled WSUDs in an urban catchment.

This thesis aims to develop new models of two WSUD technologies: green roofs and infiltration trenches/soakaways. In particular the thesis has the following objectives:

1. To identify and develop new models of green roofs and infiltration devices relevant for urban drainage applications, and integrate them into urban hydrological models.
2. To quantify the long term hydrological performance of green roofs and infiltration devices using a statistical analysis of WSUD performance.
3. To model the interaction of infiltration based WSUDs with groundwater.
4. To assess a new combination of different WSUD techniques for improved stormwater management.
5. To model the impact of a widespread implementation of multiple soakaway systems at the catchment scale.
6. Test the models by simulating observed data describing the performance of single WSUD units, and the performance of multiple systems at a catchment scale.

To address these aims, new models of green roofs and soakaways are developed and tested using observations from several urban catchments. The models are used to quantify the hydrological performance of single devices relevant for urban drainage applications. Moreover, the coupling of soakaway and detention storages is also modeled to analyze the benefits of combining different local stormwater management systems.

These models are then integrated into urban drainage network models and groundwater models in order to analyze the impact of stormwater infiltration and local detention on drainage networks and groundwater flows.

Results show that soakaways/infiltration trenches and green roofs significantly reduce annual stormwater runoff. Annual runoff from green roofs is 43-68% of the incoming rainfall and 0-62% for soakaways. Peak flow and volume reductions during single events are also quantified as a function of the return period.

Using a part of a soakaway as detention storage significantly improves its ability to reduce single event peak runoff without significant changes to its annual performance. Peak flow and annual runoff reductions are quantified for different soakaway and detention volume combinations. These systems also avoid problems of sewer network surcharge in a small catchment during a 10 year return period event.

The thesis quantifies the hydrological performance of infiltration devices interacting with groundwater. A threshold distance between infiltration devices and groundwater is estimated in order to classify whether infiltration devices are affected by groundwater or not. The threshold distance is determined as function of the soil hydraulic conductivity and the storage volume of the infiltration device. For instance, it is shown that in clay soils, infiltration trenches must be more than 11-12m above the water table if they are to be fully effective.

Widespread stormwater infiltration leads to increased groundwater recharge and the risk of groundwater flooding in areas with shallow groundwater. The increased occurrence of groundwater seepage above terrain is quantified in a case study by a catchment hydrological model that is calibrated to observations. Moreover, the performance of existing stormwater infiltration systems is affected by landuse changes in other parts of their catchment. These changes were quantified for the case study by a model and observations over a 20 year period. It was shown that urbanization with widespread stormwater infiltration increased the risk of groundwater flooding.

WSUDs are useful technologies for controlling urban stormwater runoff and the models presented in this thesis can help by simulating their hydrological impact. Careful engineering design is required to ensure that optimal results are achieved and to avoid unexpected outcomes such as increased groundwater flooding.

Dansk sammenfatning

Alternative metoder til håndtering af regnvand i byer, ofte benævnt som LAR (Lokal Afledning af Regnvand), bliver implementeret i stigende grad, fordi de forventes at kunne reducere oversvømmelser, styre afstrømning, forbedre vandkvalitet og erstatte drikkevand ved f.eks. tøjvask og havevanding. LAR-elementer er ofte små, decentraliserede enheder der håndterer regnvandet tæt på hvor det falder. Disse enheder interagerer med byens vandkredsløb og påvirker fordampningen, afstrømningen og nedsivningen til grundvandet. Kvantificering af disse påvirkninger for større byområder kræver komplekse og ressourcetunge modeller. Derfor er der brug for nye modelværktøjer. Disse værktøjer skal være simple nok til at kunne beregnes hurtigt, samtidig med at de leverer en tilstrækkelig beskrivelse af den hydrologiske respons som LAR-elementer forårsager. Værktøjerne skal både kunne simulere effekten af enkeltstående Lar-elementer såvel som koblinger af forskellige typer LAR-elementer.

Det overordnede formål med denne afhandling har været at udvikle nye modelværktøjer for to LAR-teknologier: grønne tage og faskiner. De specifikke mål med projektet var, at:

1. Identificere og udvikle nye modeller for grønne tage og faskiner, der er passende til formålet (håndtering af regnvand i byer), og integrere de nye modeller i modeller for urban hydrologi.
2. Kvantificere den langsigtede hydrologiske effekt af grønne tage og faskiner ved hjælp af statistisk analyse af resultater fra langtidssimuleringer med de nye modeller.
3. Modellere vekselvirkningen mellem infiltrationsbaserede LAR-elementer og grundvandet.
4. Evaluere en ny kombination af LAR-elementer.
5. Modellere effekten af en omfattende implementering af forskellige infiltrationsbaserede LAR-elementer i et stort opland.
6. Teste modellerne ved at sammenligne simuleringsresultater med observerede data for henholdsvis enkeltstående LAR-elementer og omfattende implementering af LAR-elementer i et stort opland.

Disse mål er opnået ved at udvikle nye modeller for grønne tage og faskiner og teste dem mod observationer fra flere forskellige urbane oplande. Modellerne blev anvendt til at kvantificere den hydrologiske effekt af enkeltstående LAR-elementer som er relevant ift. håndtering af regnvand i byer. Desuden blev modellen for

faskiner koblet med en model for forsinkelse for at undersøge fordelene ved at kombinere forskellige LAR-elementer.

Modellerne blev derefter integreret i afløbssystemsmodeller og grundvandsmodeller for at undersøge effekten af nedsivning og lokal forsinkelse af regnvand på afløbssystemer og grundvandsstrømninger.

Resultaterne viser at faskiner og grønne tage kan nedsætte den årlige regnvandsafstrømning signifikant. Afstrømning fra grønne tage svarer til 43-68% af den årlige nedbør, mens afstrømning fra faskiner svarer til 0-62% af den årlige nedbør. Vi har også kvantificeret reduktionerne i maksimal afstrømning og i afstrømmet volumen under enkelthændelser som funktion af hændelsens gentagelsesperiode.

Afsættelse af en del af faskiners volumen til forsinkelsesformål giver en signifikant forbedring af deres evne til at reducere maksimal afstrømning under enkelthændelser, uden at reducere signifikant deres effekt på den årlige vandbalance. Vi har kvantificeret reduktionerne i maksimal afstrømning og i afstrømmet volumen under enkelthændelser som funktion af forskellige kombinationer af volumen til hhv. nedsivning og forsinkelse. Nogle af kombinationerne var tilstrækkelige til at fjerne problemer med opstuvning til terræn ved en 10-års regn i et mindre opland.

Vi har også kvantificeret den hydrologiske effekt af faskiner der interagerer med grundvandet. Vi har estimeret en kritisk afstand mellem faskine og grundvandsstand, der kan bruges til at klassificere hvornår en faskines effekt bliver påvirket af grundvandet. Den kritiske afstand afhænger af jordtypen og faskinens volumen. I lerjord, f.eks. skal faskinen ligge mere end 11-12 m over grundvandsspejlet for at være fuldt effektive.

Omfattende implementering af nedsivningsbaserede LAR-elementer forårsager øget grundvandsdannelse og øget risiko for uønsket stigning af grundvandsstanden i områder med højtliggende grundvand. Vi har kvantificeret stigningen i tilfælde af grundvand der stiger op på terræn i et caseområde ved at benytte en integreret hydrologisk model for oplandet, som blev kalibreret mod observationer fra området. Modellen viser også at effektiviteten af eksisterende nedsivningselementer påvirkes af ændringer i arealanvendelse i andre dele af oplandet.

LAR-teknologier er nyttige til håndtering af regnvand i byer, og de modeller vi præsenterer i denne afhandling kan hjælpe med at forudsige deres hydrologiske effekt. Det er dog vigtigt at gennemtænke designet af LAR-teknologier for at opnå optimal effekt og for at undgå uønskede effekter som forhøjet grundvandsstand.

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1. Introduction

1.1. The hydrological impact of urbanization

Urbanization, where green areas are converted into a built environment leads to large changes in the natural hydrological cycle. The development of artificial impervious surfaces increases the surface runoff and reduces groundwater recharge due to both a reduced rainwater infiltration into the soil and a reduced amount of evaporation and transpiration through plants. Moreover, urbanization increases stormwater runoff peaks and volumes and reduces the time delay between peak rainfall and peak runoff when compared to natural areas (Bengtsson, 2005). This increases the risk of flooding and has also major implications for water quality.

Urban drainage infrastructure and artificial wastewater treatment are thus required to manage the increased stormwater runoff from urban areas. The cost of sewer systems and treatment plants is generally high (State of the Nation, 2012) and current urban drainage systems only have a limited capacity to deal with flooding. Moreover, climate change will increase the risk of flooding from sewers in urban areas (Larsen et al., 2009; Zhou et al., 2012).

There are several other consequences associated with urbanization. It can impact the local climate (Bornstein and Lin, 2000) and often leads to an over-exploitation of surface water and groundwater that may cause problems of seawater intrusion, subsidence, and depleted streams and wetlands (Morris et al., 1997). The construction of subsurface pipe networks such as water mains and sewers modifies the natural pathways of groundwater recharge and discharge. Foster et al. (1994) and Lerner (1987, 1990) reported an increase of urban recharge due leaking mains, leaking sewers, and waste water disposal. Carcia-Fresca et al. (2004, 2005) described several case studies and showed that urbanization often leads to an increased groundwater recharge.

1.2. Water Sensitive Urban Design

Alternative urban water management approaches have developed over the last few decades and it is now widely accepted that conventional urban water management approaches are not suited to addressing current and future sustainability issues (Butler and Maksimovic, 1999; Newman, 2001; Ashley et al., 2003, 2005; Wong and Brown, 2009). The pursuit of sustainability aims at initiatives for protecting and conserving natural resources and promoting lifestyles, and their supporting infrastructure, that can endure indefinitely because they are neither depleting resources nor degrading environmental quality (Wong & Eadie 2000). Water Sensitive Urban Design (*WSUD*) [1] was described by Lloyd et al. (2002) as a "philosophical approach to urban planning and design that aims to minimize the hydrological impacts of urban development on the surrounding environment."

Stormwater management through *WSUD* aims to provide flood control, flow management, water quality improvements and opportunities to harvest stormwater for non-potable uses (Fletcher et al., 2015).

WSUD systems (*WSUDs*) are increasingly being used. For example, in Denmark WSUDs were included in the official climate adaptation plan of the city of Copenhagen (City of Copenhagen, 2012) which emphasizes the need for local stormwater management. *WSUDs* typically employed in Denmark include infiltration trenches and soakaways (see Figure 1), detention basins, green roofs, rain gardens, permeable pavements and swales.

The optimal choice of *WSUDs* is complex and depends on factors such as climate, rainfall patterns, geology, aesthetics, physical space and costs. Research on *WSUDs* is necessary to assess their feasibility and to address societal needs.

Figure 1. Construction stage of an infiltration trench in Nørrebro (Copenhagen). Photo from December 2014.

1.2. Why source control?

Stormwater source control was introduced to drain developed areas in a more natural way by exploiting local storage and the infiltration capabilities using systems such as WSUDs.

[1] Similar acronyms are: Best Management Practices (BMPs), Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID), Green Infrastructure (GI), Stormwater Control Measures (SCMs), Lokal Afledning af Regnvand (LAR). See Fletcher et al. (2014).

WSUDs have several benefits when compared to traditional piped sewer systems. The benefits of WSUDs can be divided into 3 different areas: quantity, quality and amenity and biodiversity (Woods-Ballard et. al, 2005). This thesis deals with the water quantity aspects.

WSUDs reduce peak urban runoff and thus the probability of flooding and erosion of natural water-courses where stormwater is discharged. Generally, there are two types of conventional sewerage systems: a *combined sewer* in which stormwater runoff and wastewater flow together in the same pipe, and a *separate system* in which wastewater and stormwater are not mixed and flow in separate pipes. If the sewer system is combined, WSUDs reduce the water volume entering the sewer system, resulting in fewer events where untreated sewage is discharged into nearby water bodies (combined sewage overflows - CSOs) leading to a degradation of their chemical and ecological status (Chocat et al. 2007). Moreover the running cost of sewage treatment is reduced with smaller sewage volumes; the reduction in erosion improves the quality of the watercourse and WSUDs themselves can improve the quality of the runoff water by sedimentation, filtration or biological action. WSUDs can also enhance recharge and baseflow to streams (Dillon, 2005).

Figure 2 shows some of the main hydrological processes that were simulated and quantified in this thesis. Figure 2a shows the pre-development conditions with the processes of rainfall, recharge and evapotranspiration (*ET*). Figure 2b shows an example of urbanization using a conventional stormwater management approach made of a piped system. Here (compared to Figure 2a) *ET* and recharge decrease due to the presence of impervious areas. Figure 2c shows an example of the retrofitting of green roofs and infiltration trenches on the urbanized area of Figure 2b. Here (compared to Figure 2b) *ET* increases due to green roofs, recharge increases due to stormwater infiltration from infiltration trenches and stormwater runoff to the piped system decreases because of the increased *ET* and recharge.

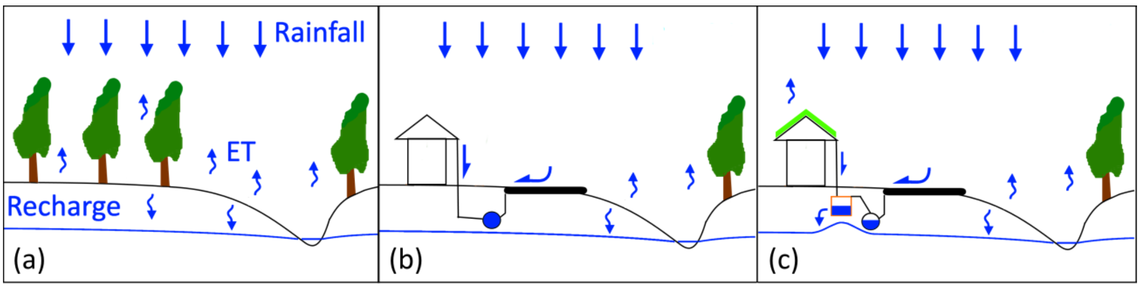

Figure 2. Representation of some of the main hydrological processes involved in the urbanization process. (a) Pre-development conditions. (b) Urbanization with a

conventional stormwater management approach. (c) Example of retrofitting green roofs and infiltration trenches.

1.3. Modelling of source control measures

The hydrological performance of WSUDs depends on many parameters, such as climate, rainfall patterns, geology and design of the device. Moreover when implemented at a larger scale they interact with the existing drainage infrastructure and the local hydrological conditions, such as groundwater, surface water and evapotranspiration. To be able to predict the hydrological impact of WSUDs, accurate models are essential (Dietz, 2007).

Several challenges in the modeling of WSUDs have been identified in the literature. Elliott et al. (2007) reviewed the models available to simulate the hydrological performance of WSUDs and urban drainage systems. They showed that current models often inadequately describe the impact of WSUDs on the urban catchment due to the poor representation of the urban hydrological cycle and also mentioned the need for improved methods for spatial and temporal model aggregation of WSUDs. There is a need for an adequate framework that enables the integration and linkage of existing models at different spatial and temporal scales and with different levels of complexity within the urban catchment (Schmitt and Huber, 2006). Generally, there is a need for more integrated modeling approaches that can consider the whole urban water cycle (Schmitt and Huber, 2006; Bach et al., 2014).

Overall, there is a need for models that can be used for urban drainage applications that aim to quantify the hydrological impact of WSUDs in the urban areas. Urban drainage applications often require continuous simulations of multiple events, multiple WSUDs systems and multiple urban hydrological processes. This requires simple and computationally efficient models.

An increasing number of studies addresses the impact of implementing WSUDs at the urban scale. There is an overall tendency to include more hydrological processes into urban catchment studies. However, most of these models cannot be validated because of the lack of data from urban areas where WSUDs are widely used. Ongoing research is trying to address these issues.

1.4. Aim of the thesis

The aim of this PhD thesis is to model the hydrological impact of WSUDs on urban hydrological and drainage flows at both the local scale and the catchment scale. The thesis analyses green roofs, retention-detention units, soakaways, infiltration trenches and soakwells. The hydrological impacts are quantified in terms of stormwater runoff and sewer flow reductions and include the interaction with groundwater.

The PhD study has the following objectives:

1. To identify and develop new models of green roofs and infiltration devices relevant for urban drainage applications, and integrate them into urban hydrological models.
2. To quantify the long term hydrological performance of green roofs and infiltration devices using a statistical analysis of WSUD performance.
3. To model the interaction of infiltration based WSUDs with groundwater.
4. To assess a new combination of different WSUD techniques for improved stormwater management.
5. To model the impact of a widespread implementation of many soakaway systems at the catchment scale.
6. Test the models by simulating observed data describing the performance of single WSUD units, and the performance of multiple systems at a catchment scale.

The thesis develops models and applies statistical analysis to quantify key hydrological processes related to use of WSUDs both at the local scale and at the catchment scale. Figure 2c shows some of the main hydrological processes considered in this thesis.

1.6. Thesis structure

Chapter 2 reports state-of-the-art and the proposed models of infiltration devices and green roofs. The models are described and discussed based on their different purposes. This chapter is linked to the first and sixth objective presented above.

Chapter 3 summarizes the hydrological performance of green roofs, infiltration trenches and combination of multiple devices. This chapter is linked to the second, third and fourth objective of the thesis.

Chapter 4 reviews models that include WSUDs in large scale hydrological models and includes two case studies. This chapter is linked to the fourth, fifth and sixth objective of the thesis.

Chapter 6 provides the overall conclusions and relates them to the objectives of the thesis. Recommendations for future research are presented in Chapter 7.

2. Green roof and infiltration device models for single units

Several hydrological models of green roofs and infiltration trenches are found in the literature. Each model was developed for a different purpose and thus included a different level of complexity (Lerer et al., 2015). Most of the models are physically based and derived using mass balance principles.

This chapter outlines the main features of green roof and infiltration device models and what needs to be considered when choosing an appropriate model type. This chapter considers Objective 1 and 6 of the thesis.

2.1. Models of green roofs

During rainfall events the most important hydrologic mechanisms in green roofs are the interception of rain by the vegetation layer, infiltration and retention/detention in the soil substrate, and retention/detention in the drainage layer. Any water in excess of the storage capacity will be drained into an outlet and during non-rainy periods water stored in the green roof is lost through evapotranspiration.

Simple models generally represent a green roof as a single or multiple lumped storage compartment that simulates the retention capacity of the vegetation layer, soil layer and drainage layer of the system (Locatelli et al., 2014 - Paper I; Stovin et al., 2013; Sherrard et al., 2012). Due to the generally high infiltration capacity of green roofs these models assume that infiltration rates equal the rainfall intensity and percolation through the soil is assumed to be instantaneous.

Potential evapotranspiration is often set as a model boundary load and can be calculated using different formulations (such as the Penman-Monteith or Thornthwaite equations; Allen, 1998; Wilson, 1990) with observed weather variables (temperature, relative humidity, atmospheric pressure, wind speed and solar radiation) as inputs (Kasmin et al. 2010; Locatelli et al. 2014 – Paper I). Alternatively, pan evaporation measurements can be used as potential evapotranspiration. Different coefficients are then applied to calculate the actual evapotranspiration rates. These coefficients (i.e. crop coefficient) can account for different roof vegetation types and for actual evapotranspiration rates that are also dependent on the moisture content of the green roof.

The main differences between modeling approaches are found in the methods used to simulate the runoff from green roofs. Simple models include the unit hydrograph approach (Villarreal and Bengtsson, 2005), the Curve Number method (Carter and Jackson, 2007), empirical relations from observations (Bengtsson, 2005; Moran et al., 2005) or the linear/non-linear reservoir method (Locatelli et al., 2014 - Paper I.; Zimmer 1997, Kasmin et al. 2010; Stovin et al., 2015). More complex models describe the infiltration process and water movement in the soil of the green roof using Richards' equation (Richards, 1931), a non-linear partial differential equation describing water movements in porous media. Both uniform one-dimensional flow (Hilten et al., 2008) and distributed two-dimensional cross section models (Palla et al., 2009) have been presented.

Simple models generally require low computational power and few parameters and therefore they are suitable for modeling of several green roofs, multiple rain events and for integration into urban hydrological models. More complex models generally require more parameters and greater computational power due to the fine spatial and temporal discretization needed to solve the non-linear partial differential equations. These models are more detailed and therefore they can be useful to analyze more processes like different roof geometries, different slopes, the interaction among multiple material layers and moisture distribution in the green roof.

Most of the models available in the literature were made with the purpose of analyzing the hydrological performance of single green roofs. Nevertheless, there is an increasing need to predict the impact of green roofs at a larger scale. This can be done by integrating green roofs into urban drainage models. This thesis (Locatelli et al., 2014 – Paper I) developed a simple green roof hydrological model to be integrated into urban drainage models. The conceptual model is shown in Figure 3 and its main characteristics are summarized in the following (the details are shown in Locatelli et al., 2014 – Paper I). Rainfall is intercepted by the vegetation layer of the green roof that is referred to as surface storage and S_{max} indicates its maximum capacity. When the maximum surface storage is exceeded, the effective precipitation P_{eff} is driven as infiltration into the subsurface storage. The volume of water that can be stored both in the green roof substrate and in the drainage layer (and eventually other built-in layers) is referred to as subsurface storage R. From the *subsurface storage*, Q_{ss} is diverted into the detention layer from which the runoff is calculated based on non-linear reservoir equations. The capacity of the different storages is continuously re-established through evapotranspiration and runoff. This model requires little computational power and can be used with a fine temporal resolution so that both the single events and the long term hydrological performance can be simulated.

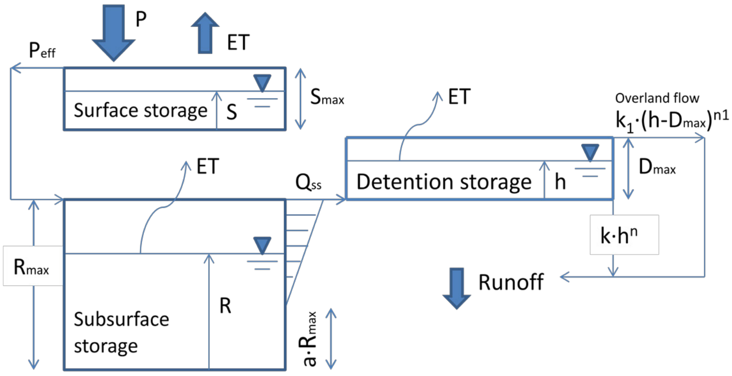

Figure 3. Conceptual hydrological model of a green roof. From Locatelli et al. (2014 – Paper I).

2.2. Models of infiltration devices

Infiltration devices such as soakaways and infiltration trenches collect the stormwater runoff from impervious areas and infiltrate it into the soil, and if the volume of water exceeds the capacity of the system, overflow to terrain, to a sewer or to a drain occurs. A schematic representation of an infiltration trench together with a local groundwater mound is shown in Figure 4. Model challenges are mainly related to the description of unsaturated and saturated flow processes and how these affect the infiltration rates from infiltration devices.

Infiltration devices experience clogging and infiltration rates decrease over time due to deposition of fine particles at the interface with soil. Generally, models represent the infiltration devices as a storage volume that depends on the porosity of the filling material and the geometry of the system and the infiltration processes can be described by either simple or more complex models.

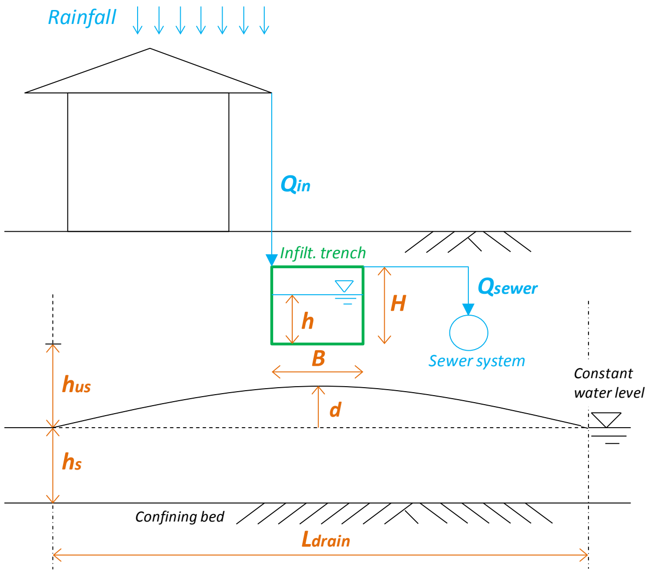

Figure 4. Sketch of an infiltration trench with a local groundwater mound. From Locatelli et al. (2015 - Paper IV).

Simple infiltration models assume a gravity driven flow described by Darcy's law (Darcy, 1856). They simulate infiltration rates as a linear function of either the wetted area or the water level in the system (Stahre and Urbonas, 1990; Mikkelsen, 1995, Bergman et al., 2011) and as a function of a conductivity parameter that is often assumed to be equal to the hydraulic conductivity of the surrounding soil. There are several other simplified models that can account for unsaturated and saturated flow processes. These models describe infiltration through simplified 1-D or 2D infiltration patterns (Browne et al., 2008; Browne et al., 2012); using the Green-Ampt equation (Green and Ampt, 1911) (e.g. Freni et al., 2009); using an exponential decay model similar to Horton's infiltration model (Horton, 1933) (e.g. Papa and Adams, 2005) and models that express infiltration as a function of the distance to the groundwater mound formed below the infiltration device (Roldin et al., 2013 – Paper III).

More complex models simulate the infiltration rates based on 2-D or 3-D computational grids (Duchene et al., 1994; Korkmaz et al., 2006) and solve the Richards' equation (Richards, 1931).

Clogging was mostly simulated using simple models, like assuming infiltration only from the sides of the infiltration device (infiltration only from the bottom can also be used as shown by Roldin, 2012) since the bottom is assumed to be almost impermeable due to fine particle deposition (IDA, 1994; BRE, 1991). Many other studies proposed simple empirical models of clogging (e.g. Lindsey et al., 1992; Deschene et al., 2004; Siriwardene et al., 2007; Bergman et al., 2011).

Simple models generally require few parameters and have low computational cost and are therefore suitable for modeling of multiple infiltration systems, multiple rain events and for integration into urban hydrological models. However they often omit other relevant processes such as the interaction of infiltration devices with groundwater (Dietz, 2007). More complex models generally require more computational power and parameters, however they are useful to analyze a larger number of processes such as moisture variations in the soil surrounding the system, unsaturated and saturated flow processes and the effect of soil heterogeneity and macropore flows (Bockhorn et al., 2015). Often simple models are capable of capturing the hydrologic behaviors of more complex models (Bockhorn et al. 2015).

Like for green roofs, most of the models available in the literature were made with the purpose of analyzing the hydrological performance of single infiltration devices. Nevertheless, there is an increasing need to predict the impact of infiltration devices at a larger scale by integrating them into urban drainage models. Particularly, there is a need to simulate the mutual interaction of infiltration trenches and groundwater, since stormwater infiltration increases groundwater levels leading to groundwater seepage above terrain and reduced performance of infiltration devices. This thesis (Roldin et al., 2013 – Paper III) presented a simple soakaway model to be integrated into urban drainage models that also account for the reduction of infiltration rates due to local groundwater mounding below the infiltration devices (see Figure 4). This model requires low computational power, has a fine temporal resolution that can simulate both single events and long term hydrological performance relevant for urban drainage applications.

2.3. Modelling combinations of WSUDs

Infiltration devices are intended to increase the annual infiltrated volume, but have limited capacity to reduce the peak flows associated with high rain intensity events, particularly when installed in poorly conductive soils (Locatelli et al., 2015 – Paper IV). Similarly, green roofs were shown to lead to a significant annual runoff reduction and a limited peak reduction during high intensity rain events. Since WSUDs have different hydrological characteristics, it is possible to combine them to achieve better performance. The literature shows an increasing number of studies that combine multiple infiltration devices at different scales (Lee et al., 2012).

This thesis (Locatelli et al., 2015 – Paper II) showed how to model the combination of soakaways and detention storages. Soakaways can contribute by reducing annual runoff, and detention storages can be used to reduce peak flows. The developed model is very simple and it combines the soakaway model of Roldin et al. (2012b) with a detention storage that fills when the soakaway maximum capacity is exceeded. The detention storage discharges a specified maximum flow rate to the sewer system (through the valve of Figure 5). Figure 5 shows the layout of the coupled soakaway and detention storage.

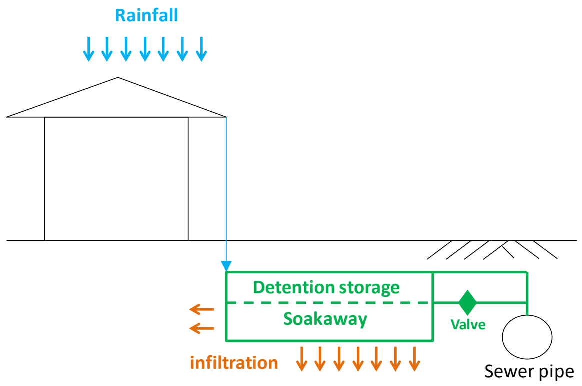

Figure 5. Sketch of the coupled soakaway and detention storage (retention-detention unit). From Locatelli et al. (2015 – Paper II).

2.4. Spatial and temporal discretization

The spatial and temporal discretization of hydrological models for single WSUDs is generally a modeler's choice. This choice mainly depends on the purpose of the study, the computational power available and the simulated processes. Spatial and temporal discretization are often related to each other, particularly when using numerical methods for solving partial differential equations. For example, many numerical methods must satisfy a Courant number condition, which restricts the ratio of the size of the time and spatial discretization (Courant et al., 1967).

Spatial discretization is mainly a function of the extent of the model area, the level of detail needed to describe the hydrological processes involved, and the computational power available. 2D models based on Richards' equation require small element sizes (Celia et al., 1992). However, spatial discretization is not an issue when using simple lumped models for WSUDs since a single unit is modeled as a single element.

Temporal discretisation depends on the spatial discretization when using model grids that solve Richards' equations. A fine spatial discretization (in the order of centimeters) generally requires small time steps (in the order of seconds). However, when using simplified models, the time step can often be adjusted to suit the purpose of the model, the simulation period, the number of simulations to be executed, the available computational power, and the time scale of the processes. If the goal is to analyze peak flows and single events in the context of urban drainage then the time step must be small, models in the literature have been run using time steps between 1 and 10 minutes (Villarreal et al., 2005; Locatelli et al., 2015 – Paper IV; Kasmin et al., 2010). The model time step should be equal to or smaller than the peak period of interest, i.e. if we are analyzing 10-minutes peaks then the model time step should be smaller than 10 minutes. If the goal is to analyze annual water balance then the time step can increase significantly, with up to daily time steps (Sherrard and Jacobs, 2012), however daily time steps can overestimate WSUD performance due to flattening of the inflow hydrographs (Locatelli et al. 2015 - Paper IV).

The green roof, infiltration device and combined device models presented in this thesis focused on urban drainage applications and they used time steps of less than 10 minutes. Generally 1 minute or smaller time resolution was considered to be optimal (Locatelli et al. - Paper I, Paper II), however when computational time was long, the time step was increased to 10 minutes (Locatelli et al., 2015 - Paper IV) or even 20 minutes (Locatelli et al., Paper V).

2.5. Integration of multiple models

Models of different processes are often combined in an integrated model framework. Integrated models refer to models that are designed to be included into a larger model framework. Elliott et al. (2007) presented a review of urban drainage models that can integrate WSUDs. For instance WSUDs models were included into urban drainage models (Roldin et al., 2013) or into groundwater models (Locatelli et al., Paper V).

Models can exchange information in two different ways, either sequentially or bi-directionally (Schmitt and Huber, 2006). Figure 6 illustrates the two concepts.

Locatelli et al. (2014 – Paper I) showed that it is important to model the hydrological performance of single green roofs using a bi-directional approach. This is because the processes of evapotranspiration, storage and runoff were shown to be highly interconnected with each other. Nevertheless, when green roofs are integrated into urban drainage models, the interaction is mostly unidirectional, i.e. green roofs affect the drainage system and not vice versa. This means that a sequential approach can be acceptable when simulating green roofs in an urban drainage model.

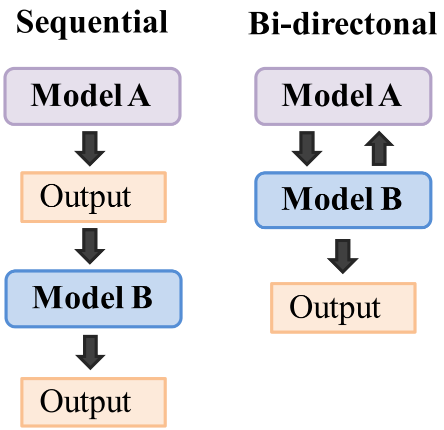

Figure 6. Illustration of the sequential and bi-directional conceptual model framework. Picture from Roldin (2012).

Single infiltration device models typically use the sequential approach to calculate infiltration rates as a function of the unsaturated flow processes (Duchene et al., 1994; Guo, 1998; Browne et al., 2012) or as a function of unsaturated and saturated flow processes (Maimone et al., 2011; Roldin et al., 2013 – Paper IV). Roldin et al. (2013 – Paper III) used a sequential approach to simulate soakaway infiltration rates that are dependent on the varying groundwater level below the soakaway. Generally, infiltration devices interact with both the drainage systems and the groundwater, thus it is relevant to use a simultaneous approach. Locatelli et al. (Paper V) presented a simultaneous approach to simulate the mutual interaction between infiltration devices and groundwater at a large scale.

Overall, if the modeled hydrological processes are interacting with each other a bi-directional approach is to be preferred, else a sequential approach is acceptable.

3. Stormwater runoff reduction of single WSUD devices

It is important to quantify the hydrological performance of single WSUD units before simulating multiple WSUDs at a catchment scale. This chapter considers the second, third and fourth objective of the thesis.

The hydrological performance of individual WSUDs has been extensively documented by experimental and modeling studies from different parts of the world. Hydrological performance is typically evaluated in terms of stormwater runoff reduction, commonly quantified in terms of long term (i.e. seasonal, annual or multi-annual) and/or single event (i.e. peak flows and volume) runoff reduction for selected rainfall events or for selected seasons or years.

In this chapter a new approach is employed, where statistical analysis of long term continuous simulation is used to quantify the hydrological performance of WSUDs. The statistical analysis employs the probability of occurrence (return period) of rainfall and runoff events. The corresponding hydrological performance is then quantified in terms of single event peak and volume runoff reductions and annual runoff reductions. Peak reduction is defined to be the ratio between the maximum peak runoff and the maximum rainfall intensity during single rainfall events. Single event volume reduction is defined to be the ratio between the single event runoff volume and the incoming rainfall. Annual runoff reduction was defined to be the ratio between annual runoff volume and annual rainfall. Both runoff and rainfall were normalized by the impervious area. This approach is useful to quantify key hydrological performances that are relevant for urban drainage applications.

3.1. Quantifying runoff reduction of green roofs

Several studies have quantified the stormwater runoff reduction of green roofs. Experimental approaches have determined annual stormwater runoff reduction using runoff observations from full scale green roofs (Bengtsson et al., 2005; Mentens et al., 2006; Voyde et al., 2010) and pilot scale green roofs (Stovin et al., 2012; VanWoert et al., 2005). Other studies have employed models together with experimental observations (Stovin et al., 2013; Locatelli et al., 2014 - Paper I).

Single event peak and volume reductions have also been determined using observations from full scale green roofs (Villarreal and Bengtsson, 2005;

DeNardo et al., 2005); from pilot scale green roofs (Carter et al., 2006; Moran et al., 2005) and from models together with observations (Locatelli et al., 2014 - Paper I; Palla et al., 2009; Stovin et al., 2013). Peak delay is also a relevant hydrological performance indicator for green roofs (Stovin et al., 2012).

This study (Locatelli et al., 2014 – Paper I) quantified the single event and annual runoff reduction of green roofs and classified the hydrological performance for different ranges of return period. The novelty of this study is the use of statistical analysis of long term continuous simulations to quantify the hydrological performance of green roofs. A simple model was run continuously for 20 years using a time step of 1 minute. The model was run for three datasets of 3 different extensive green roofs. Figure 7 shows the simulated 10 minutes peak reduction as a function of different return periods. The peak reduction of high intensity rainfall events (5-10 year return period) is 10-36% and 40-82% for low intensity rainfall events (0.1-1 year return period). Volume reduction during single events was found to be relatively limited (below 32%) because of the small storage capacity of the simulated extensive green roofs.

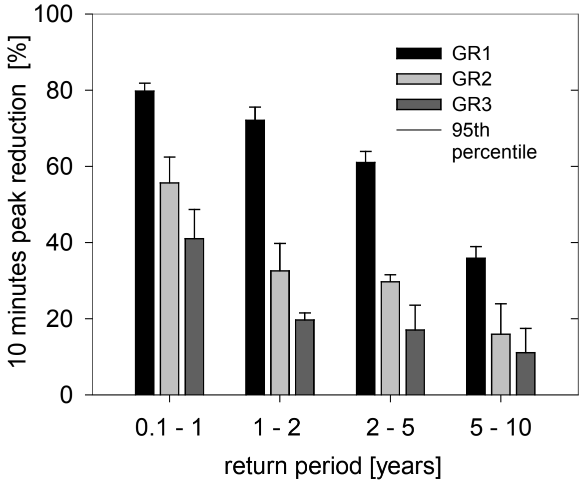

Figure 7. 10 min peak reductions per event as a function of different return periods. From Locatelli et al. (2015 - Paper I).

Results also showed that green roofs can significantly reduce annual runoff volumes. The simulated annual runoff was between 43 and 68%. The peak delay was determined as a function of the rainfall return period with results showing a decreasing time delay for increasing return period with values between 0 and 40 minutes.

3.2. Quantifying runoff reduction of infiltration devices

Few studies in the literature have quantified the stormwater runoff reduction of infiltration units. Annual runoff reduction was quantified by Locatelli et al. (2015 Paper II and Paper III); Freni et al. (2009) and Bergman et al. (2011) while peak reduction was quantified by Campisano et al. (2011); Freni et al. (2009) and Locatelli et al. (2015 - Paper II and Paper IV).

This thesis (Locatelli et al., 2015 - Paper II and Paper III) quantified the hydrological performance of infiltration devices and estimated its uncertainty. Locatelli et al. (2015 - Paper IV) used 2 soakaway models (Roldin et al., 2012a and Roldin et al., 2013 – Paper III) to quantify the hydrological performance with and without the effect of groundwater. The 2 models were used to run 9 different scenarios that covered typical surface-near soils and soakaway dimensions. Each scenario was run for about 1000 continuous Monte Carlo simulations of 20 year length using a 10 minute time step. The Monte Carlo simulations were used to investigate the range of variability of the most influential parameters for the hydrological performance of infiltration units: soil hydraulic conductivity, geometry and storage volume, depth of the unconfined aquifer and distance between the infiltration unit bottom and the local groundwater table. A statistical analysis was used to quantify the stormwater runoff reduction based on different return periods.

Figure 8 shows the annual runoff reduction of infiltration trenches obtained with a simple soakaway model (Roldin et al., 2012b) that assumes infiltration rates to be a function of the hydraulic conductivity and the wetted area of the infiltration devices.

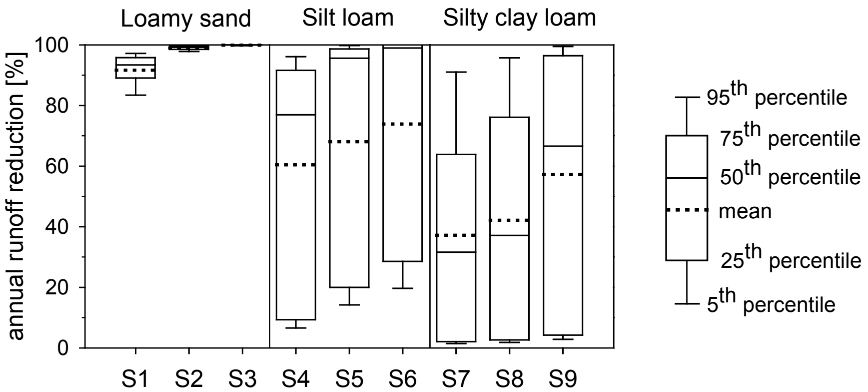

Figure 8. Annual stormwater runoff reduction for 9 scenarios (S1 to S9). The uncertainty bounds of annual runoff reduction include the effect of interannual variation and variability of

model input parameters, particularly the hydraulic conductivity. From Locatelli et al. (2015 – Paper IV).

Annual runoff reduction of infiltration trenches is shown to be 83-100% in loamy sand, 7-100% in silt loam and 2-99% in silty clay loam. The great spread of annual runoff reduction was mainly due to the variability of the soil hydraulic conductivity. The annual runoff reduction was also simulated with the model of Roldin et al. (2013 – Paper III) and results showed that the annual reduction tended to zero as the distance between the bottom of the infiltration trench and the groundwater table decreased to zero. Peak and volume runoff reduction during single events (return period of the events in the order of 5-10 years) was shown to be relatively small (below 38%), unless significant storage volumes were built. This study also showed that it is important to consider the local groundwater conditions when designing infiltration trenches, particularly when the groundwater is below a threshold distance. This distance was found to be in the order of 1-3 m for infiltration trenches in loamy sand; 6-8 m for infiltration trenches in silt loam sand and 11-12 m for infiltration trenches in silty clay loam Locatelli et al. (2015 - Paper IV). Locatelli et al. (2015 – Paper II) also estimated the stored water volume in soakaways at the beginning of rain events and showed that single event performance can be limited when there is a significant initial volume in the soakaway. The simulated volume of water in the soakaways at the beginning of rain events of more than 10 mm depth was about 17-53%.

Overall, the results quantified the effect of groundwater on the performance of infiltration devices. Infiltration trenches were shown to significantly reduce annual runoff volumes, particularly in sandy soils, and significant annual runoff reduction can be achieved with relatively small storage volumes.

3.3. Quantifying runoff reduction of retention-detention units

Some studies have analyzed the performance of multiple WSUD types at a large scale (Eric et al., 2013; Lee et al., 2012), but few studies have quantified the hydrological performance of different single devices when they are coupled together.

Locatelli et al. (2015 - Paper II), quantified the runoff reduction of a unit that combines an infiltration storage with a detention storage (a retention-detention unit, see Figure 5). The annual runoff reduction of retention-detention units was 68-100% in this case study where the soil hydraulic conductivity was 8.2·10-7 m/s. The soakaway infiltration model of Roldin et al. (2012b) was combined with a detention storage with an outlet to the local sewer system. Overall results from this study showed that using part of a soakaway as a detention volume significantly increased the peak reduction capacity, with limited impact on the annual runoff reduction of the soakaway. For instance, if 20% of a 3.3 m^3 soakaway were used as a detention volume, peak reduction would significantly increase (from 46% to 74%), whereas annual runoff reduction would slightly decrease (from 91% to 87%).

3.4. Comparison of different systems

The hydrological performance of green roofs, infiltration devices and retention-detention units can be compared using results from this thesis. The selection of WSUDs depends on the local conditions. For example, the retention capacity of green roofs is due to evapotranspiration, whereas the one of infiltration devices is due to infiltration into the soil. This means that if we are to reduce runoff in an urban area where enhanced groundwater recharge is desirable, infiltration devices could be considered; whereas if we are in an area where stormwater infiltration is limited by regulations or the soil is poorly conductive, green roofs could be an option.

It was shown that even few millimeters of storage could contribute to a significant reduction of annual runoff volumes (Locatelli et al., Paper I and Paper IV). This can be relevant for urban areas with either combined sewers (to reduce the costs of treating and pumping sewage) or separate systems (to reduce the negative impacts on the ecology and geomorphology of the receiving systems).

Table 1 shows the hydrological performance of green roofs and infiltration trenches. The table shows the average performance calculated from the results reported by Locatelli et al. (2014 - Paper I and 2015 - Paper IV). The green roof results (Locatelli et al., 2014 - Paper I) were obtained from statistical analysis of 3 different continuous simulations. The green roof model parameters for each simulation were obtained from model calibration to observed data from 3 different experimental green roofs. The infiltration trench results (Locatelli et al., 2015 - Paper IV) were obtained from 9 scenarios of about 1000 Monte Carlo simulations each. The scenarios covered typical soil types and storage volume of infiltration devices, and the Monte Carlo simulations covered the parameter variability of the different soil types, infiltration trench geometries and saturated zone thickness and distance. Locatelli et al. (2015 - Paper IV) also showed a threshold distance between infiltration trenches and groundwater to classify the so called 'Infiltration trenches far from the groundwater' and 'Infiltration trenches with shallow groundwater' shown in Table 1. This distance is in the order of 1-3 m for infiltration trenches in loamy sand; 6-8 m for infiltration trenches in silt loam sand and 11-12 m for infiltration trenches in silty clay loam Locatelli et al. (2015 - Paper IV).

A peak runoff reduction could be achieved by both green roofs and infiltration devices for low intensity rain events (0.5-1 year return period). This can be relevant for urban areas experiencing frequent local pipe surcharges, combined sewer overflows or basement flooding.

Only retention-detention units could achieve a significant peak runoff reduction for high intensity rain events (5-10 year return period). These combined systems can be useful when implementing climate change adaptation strategies in urban developments.

Stormwater runoff was shown to be reduced for both green roofs and infiltration devices and the next step is to evaluate the impacts at larger urban scales.

Table 1. Hydrological performance of green roofs and infiltration trenches. The table shows average values calculated from Locatelli et al., 2014 - Paper I and 2015 - Paper IV.

		Storage [mm]	Annual runoff reduction [%]	Single event 10 minutes peak reduction [%]		Single event volume reduction [%]	
				0.5-1 y return period events	5-10 y return period events	0.5-1 y return period events	5-10 y return period events
Extensive green roofs			56	56	27	17	3
Infiltration trenches far from the groundwater	Loamy sand	5	92	89	8	93	36
		12	99	98	36	99	68
		26	100	100	89	100	95
	Silt loam	16	60	90	9	90	12
		43	68	94	36	93	31
		64	74	95	54	95	53
	Silt loam	29	37	88	5	88	4
		43	42	89	10	88	7
		75	57	91	26	91	22
Infiltration trenches with shallow groundwater	Loamy sand	5	59	88	4	90	17
		12	66	93	18	93	31
		26	66	94	40	93	40
	Silt loam	16	32	88	4	87	5
		43	38	89	13	88	11
		64	42	90	22	89	21
	Silt loam	29	18	87	2	86	2
		43	19	87	3	86	2
		75	29	88	8	87	7

4. Modelling of WSUDs at the catchment scale

It is important to predict the hydrological impact of WSUDs on whole urban catchments. This has been documented by a number of studies where WSUD models have been integrated with urban hydrological models. Such models contain many interacting hydrological processes that depend on the local conditions and operate at different temporal and spatial scales. It is unrealistic to model all processes and better predictions do not result from including as many processes as possible. The challenge is then to identify and model the key hydrological processes for each case study.

This chapter shows how WSUDs can be integrated with urban hydrological models at an urban catchment scale, and how to model and identify the key hydrological processes. The chapter concludes with 2 modeling studies that were applied to different urbanized areas. This chapter is linked to the fourth, fifth and sixth objectives of the thesis.

4.1. Catchment scale impact of green roofs

Few studies have examined the impact of green roofs at the urban scale. Mentens et al. (2006) estimated annual stormwater runoff reduction of green roofs at the city scale by simply multiplying the estimated retention of a single green roof by the part of the city area that could potentially be covered by green roofs. This study showed that green roofs can significantly reduce annual runoff volumes in a city.

However large scale implementation of green roofs can have other impacts. For example, runoff delay in a catchment might negatively influence the downstream catchments; the reduction of stormwater runoff affects the combined sewer network response during single events; the loss of water by evapotranspiration can compete with the need of collecting stormwater runoff for non-potable uses (i.e. toilet flushing and irrigation); runoff water from green roofs might contain nutrients and other compounds that impact overall runoff water quality (Czemiel Berndtsson, 2010).

The impact of green roofs on the urban water cycle can be simulated by including green roofs in urban drainage models. For example, the model of Locatelli et al. (2014 – Paper I) can be implemented into an OpenMI framework (Gregersen et al., 2007) that is design to facilitate connections to other OpenMI compliant commercial software. Other hydrological models (such as the NAM model of DHI, 1999 and Gustafsson et al., 1999) can also be used (Locatelli et al., 2014 – Paper I).

Green roofs models coupled to urban drainage network models are useful to simulate the impact of green roof on the drainage network flows during single events and longer periods. This is relevant to predict sewer surcharge, flooding, combined sewer overflows and load to the treatment plant. Green roof models can also be coupled to other WSUDs models, for example to infiltration device models to simulate the impact of a reduced stormwater runoff (from green roofs) on the performance of the infiltration device.

4.2. Catchment scale impact of stormwater infiltration

The impact of stormwater infiltration at the catchment scale has been investigated in several studies. The implementation of stormwater infiltration at city area is constrained by existing built environment and underground infrastructure, soil pollution, groundwater levels, local drinking water assets, and the quality of the stormwater runoff (Gobel et al., 2004; Mikkelsen et al., 1995; Revitt et al., 2003). Therefore, it is important to predict the consequences of stormwater infiltration on subsurface flows and the interaction with underground structures (Dietz et al., 2007).

The impact of widespread stormwater infiltration has been examined in several studies where infiltration devices have been included in urban hydrological models. Some studies integrated infiltration devices into urban drainage models to evaluate the impact of stormwater infiltration on the urban drainage network (Roldin et al., 2012a; Semadeni-Davies et al., 2008). Other studies integrated infiltration devices into groundwater models to evaluate the impact of stormwater infiltration on recharge and groundwater levels (Jeppesen, 2010; Gobel et al., 2004; Ku et al., 1992), and groundwater flooding (Locatelli et al., Paper V). Further studies integrated infiltration devices, groundwater and urban drainage models to analyze the response of a shallow groundwater table that continuously exchange flow with the leaking drainage system (Kidmose et al., 2015). Models have also been used to simulate the interaction of multiple mounding below soakaways to predict groundwater seepage areas (Antia, 2008).

A common method to integrate infiltration devices into larger scale models is to reduce the impervious area of the catchment where the infiltration devices are located (Semadeni-Davies et al., 2008; Roldin, 2012, Kidmose et al., 2015;

Jeppesen, 2010). This means that the stormwater runoff from the impervious areas connected to infiltration devices is removed from the model (implying that the capacity of the infiltration systems is unlimited) or directly applied as groundwater recharge (implying that temporary storage in the infiltration system is zero and unsaturated flow processes are instantaneous). This method overestimates the performance of infiltration systems and may be acceptable for an approximation of the annual water balance, however it cannot reproduce other relevant processes such as backflow of water from the sewer to the infiltration device, single events response (that is dependent on the water content at the beginning of rain events) (Roldin et al., 2012b; Locatelli et al., 2015 – Paper II), and groundwater interaction (Roldin et al., 2013 – Paper III; Locatelli et al., Paper V).

Groundwater interacts with infiltration devices in different ways. Groundwater can periodically rise above the bottom of the infiltration device limiting its storage volume (Locatelli et al., Paper V). Groundwater mounds below infiltration devices decrease infiltration rates (Roldin et al., 2013 - Paper III) and multiple mounds interact with each other (Antia, 2008). Groundwater and infiltration devices affect each other by changing the local moisture conditions (Browne et al., 2012). These processes can have very localized impacts that can be hard to model at the city scale.

Roldin et al. (2012b) presented a method to aggregate multiple infiltration units. This method was used to model infiltration devices together with drainage systems to evaluate their impact on combined sewer overflows (Roldin et al., 2012a), on sewer fows (Locatelli et al., 2015 - Paper II; Elliott et al., 2009) and on groundwater levels (Locatelli et al., Paper V).

Roldin et al. (2013 – Paper III) presented a soakaway model that can be integrated into large scale hydrological models while including the effect of local groundwater mounds below infiltration units. Locatelli et al. (Paper V) coupled infiltration devices and a groundwater model to simulate the impact of stormwater infiltration devices in an area with shallow groundwater table.

4.3. Spatial discretization

Fine spatial discretization is limited by computational power; nevertheless a proper model grid should be selected to accurately represent the selected hydrological processes.

The spatial discretization used in distributed groundwater models of cities or larger scales generally employ grid cells that have a size larger than 50m

(Vazquez et al., 2002; Jeppesen, 2010; Kidmose et al., 2015). This is too large to detect localized processes such as the local mounding and local unsaturated/saturated flows processes that happen at the infiltration unit scale (Markussen et al., 2004; Maimone et al., 2011). In order to overcome this problem, sequential simulations of infiltration devices and groundwater flow have been used (Göbel et al., 2004; Maimone et al., 2011). However this solution only partly accounts for the mutual interaction between infiltration devices and groundwater.

This thesis presents some novel methods for dealing with the large range of spatial scales in urban water problems. A simplified model to simulate the local mounding and varying infiltration rates in larger scale models was presented by Roldin et al. (Roldin et al. 2013 – Paper III). This model showed that the infiltration rates are significantly affected by groundwater mounds below the infiltration devices, and that infiltration rates tend to zero as the groundwater table approaches the bottom of the infiltration device. Further, Locatelli et al. (Paper V) presented a model that integrated infiltration devices and groundwater at a catchment of 110 km^2. The spatial discretization of the groundwater flow model was 70 m and soakwells were aggregated up to areas of a few hectares. This model simulated the mutual interaction of a seasonally fluctuating groundwater table with infiltration units. The results from this model are shown later in Section 4.5.

4.4. Temporal discretization

Temporal discretization is often limited by computational power; nevertheless a proper time step must be selected to accurately represent the selected hydrological processes that can operate at significantly different time scales.

Groundwater models typically employ time steps of 3-24 hours (Jeppesen et al., 2011, Kidmose et al., 2015), whereas urban drainage models often employ time steps of less than a minute (Kidmose, et al 2015; Roldin et al. 2012a). Infiltration devices empty over time periods of a few days and typical time steps used for modeling of infiltration devices are in the range of 1-20 minutes (Locatelli et al., 2015 - Paper II and Paper IV).

Locatelli et al. (2015 - Paper IV) used a 3 hour time step for the groundwater flow model and a 20 minute time step for the infiltration devices. The 2 models ran bi-directionally and exchanged flows every groundwater time step. The 20 minutes time step was considered appropriate given that the purpose of the model was to simulate long term groundwater variations, however it is too long for urban drainage applications where time steps should be smaller than 10 minutes. Locatelli et al. (2015 – Paper II) used an adjustable time step with a maximum of 30 seconds to simulate peak flows in a drainage network during single events with different return period; and a time step of 1 minute to simulate the long term stormwater runoff reduction.

Overall, if we are to couple infiltration devices with urban drainage models, the WSUDs should be simulated with time steps that are smaller than the duration of the urban drainage peak flows of interest. When coupling infiltration devices with urban drainage models, time steps for WSUDs can be larger, depending on the scope of the study.

4.5. Case studies

This section presents 2 different case studies that analyzed the impact of WSUDs at different scales (Locatelli et al., 2015 – Paper II and Paper IV). The models developed in this section included different hydrological processes that were selected based on the local conditions and the purpose of the study.

Case study 1. Modelling the impact of retention–detention units on sewer surcharge and peak and annual runoff reduction.

Locatelli et al. (2015 – Paper II) modelled the performance of coupled soakaway and detention units (retention-detention units, see Figure 5) for a combined sewer catchment of about 0.7ha (Figure 9). This catchment has had problems with basement flooding due to high water levels in the sewer system during high intensity rain events. This was thought to be due to both the local under-dimensioned sewer pipe and to the fact that the local discharge capacity of the sewer was limited by sewage coming from the upstream parts of the catchment. The purpose of the study was to analyze whether it is possible to use combined stormwater retention and infiltration systems to achieve both stormwater runoff reduction and avoid the need for enlarged combined sewer/stormwater pipes to cope with increased stormwater flows. This study modeled both the annual runoff reduction to the sewer system and the single event impact.

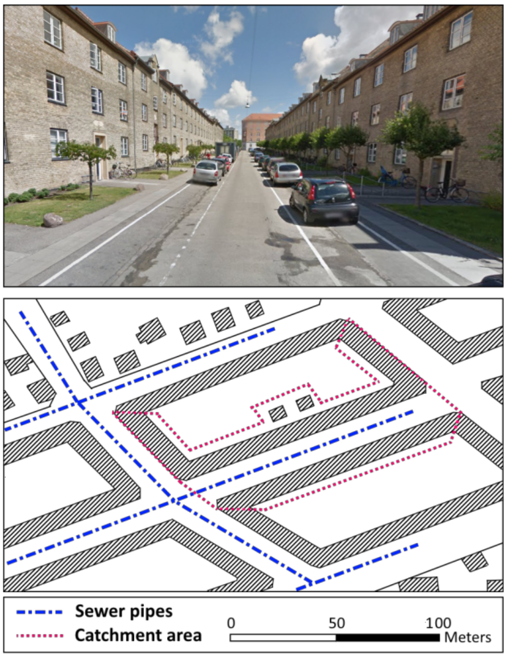

Figure 9. Case study area used to analyze the impact of stormwater infiltration and local detention storages on the urban drainage network. From Locatelli et al. (2015 – Paper II). (a) Photo of the street. (b) Plan view.

Given the purpose of the study and the local conditions the following hydrological processes were selected to be modeled: sewer network flows, rainfall-runoff, soakaway and detention storage, and infiltration from the soakaway. The groundwater table in this area is far below the terrain level so that the interaction of groundwater and infiltration devices was assumed to be insignificant.

In this study, the simple soakaway model of Roldin et al. (2012b) was coupled to a detention storage that could discharge a maximum flow rate to the local sewer system. The maximum flow that could be discharged to the local sewer was estimated using the whole urban drainage catchment model. This maximum flow rate was determined by trial and error with the aim of avoiding sewer surcharge (water above terrain level) in the analyzed catchment. Multiple devices were aggregated according to the method presented by Roldin et al. (2012b). This model was then run to continuously simulate 20 years with a 1 minute time step. The model was used to estimate annual runoff reduction and peak flow runoff reduction for different combinations of retention and detention volumes. The model was then coupled to the urban drainage model and used to run a design storm event of 4 hour duration using a time step smaller than 30 seconds. This model was used to simulate the impact of retention-detention units on peak flows in the drainage network.

Overall, this study showed how retention-detention units could be modeled to satisfy different purposes. Figure 10 shows the simulated annual runoff reduction as a function of different infiltration trench volumes. Only the soakaway (retention) volume is shown in the figure because the detention volume was found to be an insensitive parameter for annual runoff reduction (Locatelli et al., 2015 – Paper II). Overall results showed that significant annual runoff reduction (on average 77%) could be achieved even with a small soakaway volume (1.9 m^3 of infiltration trench storage per 100 m^2 of impervious drained area). The study also showed how the detention volume can be designed to avoid sewer surcharge in this area. The final design of the retention-detention unit was tested during a single rain event (of 10 year return period) simulation and the results (Figure 11) showed that the maximum water level in the sewer system during the simulation was below terrain level (the scenario without retention-detention units showed water level above terrain, see Locatelli et al., 2015 – Paper II).

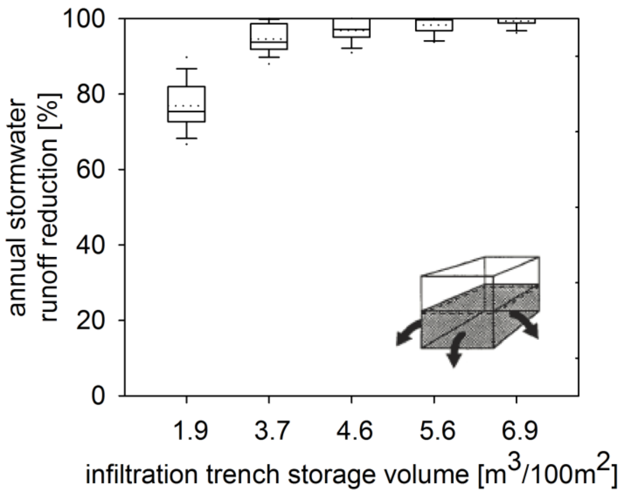

Figure 10. Simulated annual stormwater runoff reduction as a function of 5 different infiltration trench volumes (volume per 100 m^2 of connected impervious area); hydraulic conductivity = $8.2 \cdot 10^{-7}$ m/s. From Locatelli et al. (2015 – Paper II).

Different retention-detention volume combinations were also simulated and the results showed that optimum volume combinations could be obtained (Locatelli et al., 2015 – Paper II).

This study considered a small catchment without significant upscaling issues. For larger areas aggregation of single units is needed to reduce computational costs. In these cases it can be difficult to determine the spatial location and the point of connection to the drainage network of the aggregated unit. This is addressed in the next case study.

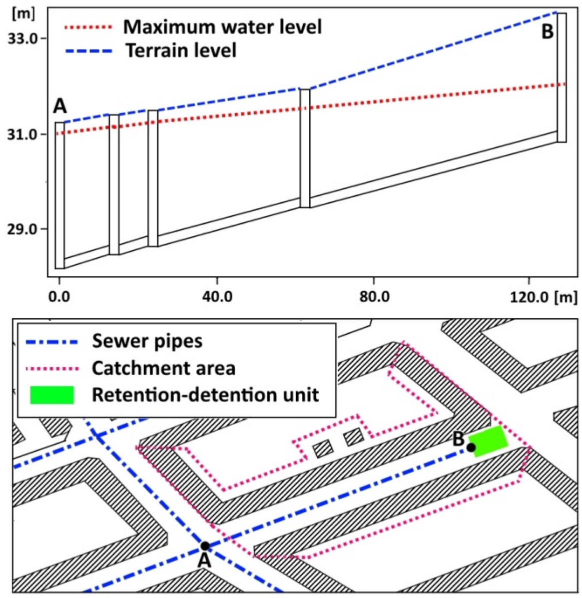

Figure 11. Simulated maximum water level observed in the sewer system during a single rain event of 10 year return period.

Case study 2. Groundwater flooding and hydrologic impacts of catchment-wide stormwater infiltration.

Locatelli et al. (2015 – Paper IV) modelled the impact of widespread stormwater infiltration on groundwater levels for a catchment of about 110 km^2 located in the south of Perth (Australia) (see Figure 12). This catchment has experienced increased groundwater flooding (where groundwater has risen to levels above terrain) because of continuous urbanization and increasing stormwater infiltration. The purpose of the study was to model the groundwater rise due to urbanization and to evaluate the reduction of infiltration device performance due to shallow groundwater levels. The novelty of the work was the use of data to test large scale urban models including WSUDs. The data includes long term observations of groundwater response in the urbanized areas where stormwater infiltration was applied.

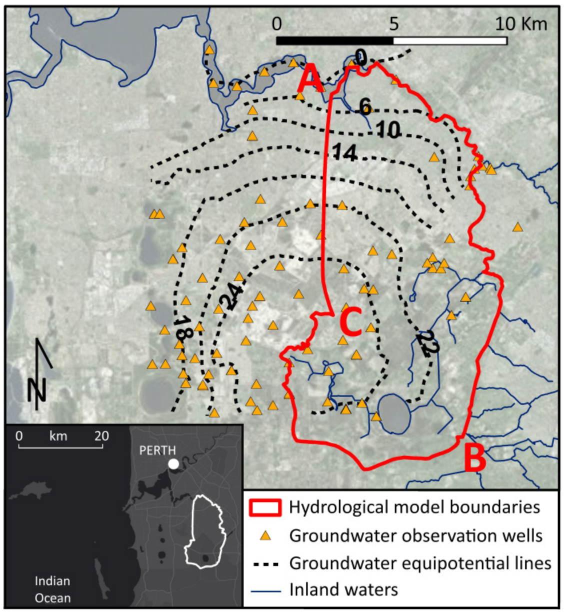

Figure 12. Plan view of the model area used to analyze the impact of widespread stormwater infiltration on groundwater levels.

Given the purpose of the study and the local conditions the following hydrological processes were selected to be modeled: saturated and unsaturated flow processes, evapotranspiration, storage and infiltration from infiltration devices and stream flows.

The model (Locatelli et al., 2015 – Paper IV) coupled infiltration units and saturated and unsaturated flow over the Perth catchment. Multiple infiltration units were aggregated according to Roldin et al. (2012b) and groundwater and infiltration units could bi-directionally interact with each other based on the local heads and a conductivity parameters (i.e. if the water in the infiltration unit is higher than the groundwater head then there is infiltration, otherwise not). The level of aggregation was shown to have a significant impact on the results, particularly the spatial location of the aggregated unit. For example, the infiltration units could be aggregated for a large area, however if they were spatially placed at a point where groundwater is close terrain then almost no infiltration occurred (and vice versa). The spatial aggregation was limited to a maximum area that was determined using the average groundwater gradients of that area.

The Perth study showed how infiltration units affect urban hydrology when implemented in large groundwater catchments. The model results showed that groundwater levels rose and increased the risk of groundwater flooding as a result of urbanization. Figure 13 shows the simulated annual maximum groundwater head at a selected location in an urban area of the catchment. The annual maximums were computed for 4 different scenarios: s2012 used the land-use map from the year 2012; s1995 used the land-use map from the year 1995; s1974 used the land-use map from the year 1974, and sDrain used the land-use map from the year 2012 and assumed that stormwater runoff from roofs is not infiltrated but removed from the model area. Figure 13 shows that the annual maximum groundwater levels increased with increased urbanization (from s1974 to s1995 to s2012). It can also be seen that sDrain is significantly lower than s2012, meaning that roof stormwater runoff infiltration significantly increases groundwater levels.

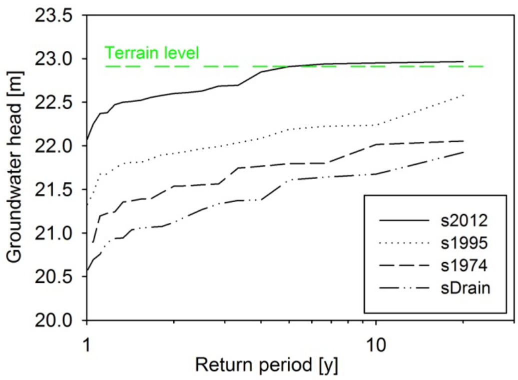

Figure 13. Simulated annual maximum groundwater head at a selected location as a function of the return period for different scenarios. From Locatelli et al. (Paper V).

The groundwater rise in the Perth catchment was due to the increased amount of recharge from direct stormwater infiltration and the reduced evapotranspiration due to a reduction of green areas. This affected the whole groundwater catchment. The results also showed that increasing groundwater levels reduce the performance of infiltration units due to the periodic rising of the groundwater levels above the bottom of the infiltration units. The reduction of annual runoff performance depends on the spatial location of the infiltration units in the catchment and it was shown to be up to 12% for some urban areas.

4.6. Discussion and conclusion

This chapter showed how to couple WSUDs models into urban drainage and groundwater models. It showed that the selection of key hydrological processes to be modeled and the proper spatial and temporal resolution must be based on the purpose of the model and the local conditions. This chapter also showed how to aggregate infiltration units into larger hydrological models.

Overall results showed how WSUDs can be relevant for stormwater management and how important it is to properly plan large scale implementation, particularly when stormwater infiltration is used in areas with shallow groundwater.

Catchment scale coupled WSUD and urban water models are complex, and more research is needed to fully understand the behavior of these systems. It is critical that models are tested against long term and large scale datasets in order to evaluate the model approach. Modelling of the uncertainty in the predictions should also be addressed.

5. Conclusion

Green roofs and infiltration devices are increasingly been installed to manage urban runoff and their hydrological impact can be predicted using models. The goal of this study was to develop new methods for modelling the hydrological impact of WSUDs at different urban scales.

WSUDs can be modeled in several ways depending on the purpose of the study. Urban drainage applications often require continuous simulations of the hydrological response of many WSUDs to multiple rain events. In order to achieve this, the WSUDs models must be computationally efficient.

The thesis developed new models of green roof and infiltration devices for urban drainage applications (Objective 1). Moreover, the WSUD models were coupled to urban hydrological models to simulate their impact on urban hydrological processes.

The thesis quantified the hydrological performance of green roofs and infiltration trenches relevant for urban drainage applications (Objective 2). Single event and annual runoff reduction were computed using a statistical analysis of long term continuous simulations. The hydrological performance of single WSUDs was quantified in terms of annual stormwater runoff reduction and single event peak and volume reduction. A method to quantify them was shown based on statistical analysis of long term continuous simulations. Results showed that extensive green roofs can reduce single event peak runoff of 5-10 year return period events up to 36% and annual runoff up to 57%. Infiltration trenches can reduce single event peak runoff of 5-10 year return period events up to 38% and annual runoff up to 100 % in sandy soils.

The thesis presented a simple model that can simulate infiltration trenches in the presence of a shallow groundwater table (Objective 3). This model was used to quantify the hydrological performance of infiltration trenches interacting with the groundwater. Moreover, a threshold distance (useful to classify whether infiltration devices are affected by groundwater or not) for infiltration trenches and groundwater interaction was determined. This distance was quantified as a function of the soil type and the storage volume of the infiltration device. For clay soil types it was found that infiltration trenches must be 11- 12 m above the water table to be fully effective, while for sand only 1.5-3 m is required.

The thesis showed how to combine infiltration units and detention devices and how to include them in an urban drainage model of an existing catchment

(Objective 4). The annual runoff and peak reduction of retention-detention units for a small catchment was then quantified, including their impact on sewer flows.

Finally, the thesis investigated the impact of infiltration devices on groundwater levels for a Perth (Western Australia) urban catchment where the impact of widespread stormwater infiltration on groundwater levels and groundwater flooding has been measured over a 20 year period (Objective 3, 5 and 6).

This thesis has shown that WSUDs are useful technologies for controlling urban stormwater and runoff. However careful design is necessary if optimal results are to be achieved and good engineering design is critical if unexpected outcomes such as increased groundwater flooding are to be avoided.

6. Recommendations and future perspectives

Based on the discussion, conclusion and the work done during this PhD study, further research is recommended within the following fields.

Integrated WSUDs hydrological models
Integrated modeling approaches that can consider the whole urban water cycle should be developed (Bach et al., 2014). Models to simulate the hydrological performance of WSUDs and models to simulate urban hydrological processes should be linked together through a flexible and simple framework that would allow the user to easily add and remove hydrological processes and model complexity based on the specific needs.

Further processes to include into urban hydrological models
In addition to these broader research perspectives for urban hydrological modelling, there are some specific technical issues that are directly related to the models developed in this thesis. The infiltration trench model of Roldin et al. (Paper III) should be coupled to groundwater models in order to account for the effect of local mounding below single infiltration trenches. Moreover, the spatial aggregation of this model to represent multiple mounds should be addressed. Other factors, such as soil heterogeneity, macro-pore flow and geological fractures that were shown to significantly impact the performance of infiltration trenches (Bockhorn et al., 2015) should be included in hydrological models. Catchment models of infiltration based WSUDs in shallow groundwater areas should incorporate both groundwater and drainage networks (Kidmose et al., 2015).

Case studies of multiple integrated hydrological processes
Further case study areas where WSUDs were implemented and observations are available from the area should be modeled trying to integrate multiple hydrological processes (Barron et al., 2012; Locatelli et al., Paper V).

Multiple WSUDs interaction
The models presented in this thesis and most of the studies available in the literature address hydrological modeling of a single kind of WSUDs, i.e. either green roofs or soakaways. It is relevant to study the interaction of multiple kind of interconnected WSUDs both among single units and at a larger scale (Lee et al., 2012).

Water quality modeling

Water quality aspects of WSUDs are also highly relevant in the context of stormwater management. It is therefore important that models of water quantity, like the ones presented in this thesis, are coupled to water quality models (Elliott et al., 2007).

Economic assessment

It is relevant to assess the economic performance of WSUDs systems in order to compare different solutions. This can be done by integrating urban hydrological models with economic models (Zhou et al., 2012).

Environmental modeling

It is relevant to estimate the environmental impact of WSUDs and compare them with other solutions. This can be done by coupling hydrological models to environmental assessment tools (De Sousa et al., 2012).

Uncertainty analysis

Understanding the uncertainty in the prediction of the hydrological performance is essential. This was partly done for the performance of single infiltration trenches. However, the uncertainty in the performance of WSUDs at a larger scale was not addressed and is considered to be highly relevant (Chang et al., 2011).

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8. Papers

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II. **Locatelli, L.**, Gabriel, S., Mark, O., Mikkelsen P.S., Arnbjerg-Nielsen, K., Taylor, H., Bockhorn, B., Larsen, H., Kjølby, M.J., Blicher A.S., Binning, P.J., 2015. Modelling the impact of retention-detention units on sewer surcharge and peak and annual runoff reduction. Water Science and Technology, 71(6), 898-903.

III. Roldin, M., **Locatelli, L.**, Mark, O., Mikkelsen, P.S., Binning, P.J., 2013. A simplified model of soakaway infiltration interaction with a shallow groundwater table. Journal of Hydrology, 497, 165–175.

IV. **Locatelli, L.**, Mark, O., Mikkelsen, P.S., Arnbjerg-Nielsen, K., Wong, T., Binning, P.J., 2015. Determining the extent of groundwater interference on the performance of infiltration trenches. Journal of Hydrology, 529, Part 3: 1360-1372.

V. **Locatelli, L.**, Mark, O., Mikkelsen, P.S., Arnbjerg-Nielsen, K., Roldin, M., Deletic, A., Binning, P.J. Groundwater flooding and hydrologic impacts of catchment-wide stormwater infiltration. Manuscript.

In this online version of the thesis, **paper I-V** are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from.

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The Department of Environmental Engineering (DTU Environment) conducts science-based engineering research within four sections:
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The department dates back to 1865, when Ludvig August Colding, the founder of the department, gave the first lecture on sanitary engineering as response to the cholera epidemics in Copenhagen in the late 1800s.

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