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MONITORING OF RAINFALL-RUNOFF FROM URBAN PERVIOUS AREAS

BY

KRISTOFFER TØNDER NIELSEN

DISSERTATION SUBMITTED 2019

AALBORG UNIVERSITY
DENMARK

MONITORING OF RAINFALL-RUNOFF FROM URBAN PERVIOUS AREAS

by

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Kristoffer started his studies at Aalborg University in 2010 and finished his Master of Civil Engineering in the summer 2015. Briefly after graduation, Kristoffer was employed at EnviDan A/S and did until the end of winter 2016 primarily work with research and development projects. Kristoffer started his PhD study the 1st of March 2016 as an Industrial PhD-student with the goal and intention to include practical applicable knowledge which can optimize decision making in urban drainage engineering.

EDUCATION AND WORK EXPERIENCE

2016 – now:	Industrial Ph.D. student at Department of Civil Engineering, Aalborg University and EnviDan A/S
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Paper I - Nielsen, K.T., Moldrop, P., Thorndahl, S., Nielsen, J.E., Uggerby, M., Rasmussen, M.R. (2019). Field-scale monitoring of urban green area rainfall-runoff processes. *Journal of Hydrologic Engineering*, DOI: 10.1061/(ASCE)HE.1943-5584. 0001795, in press.

Paper II - Nielsen, K.T., Moldrop, P., Thorndahl, S., Nielsen, J.E., Duus, L.B., Rasmussen S.H., Uggerby, M., Rasmussen, M.R. Automated physical rainfall simulator for variable rainfall on urban green areas, s*ubmitted to Hydrological Processes.*

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Dansk Vand Konference (Danish Water Conference) 2018, 13 – 14 November 2018. Presentation title: Ubefæstet overfladeafstrømning – reglen eller undtagelsen? (“Pervious surface runoff – the rule or exception?” Oral presentation).

OTHER WRITTEN KNOWLEDGE DISSEMINATION

Nielsen, K., Uggerby, M. (2016). Overfladeafstrømning fra grønne arealer (Surface runoff from green areas). *EVA-bladet (pp. 22-25)*. Link: http://www.evanet.dk/eva-blad-nr-02-juni-2016/.

Nielsen, K., Duus, L.B., Møldrup, P., Thorndahl, S.L., Rasmussen, S.H., Uggerby, M., & Rasmussen, M.R. (2017). ICUD-0061 Field station to quantify overland runoff from urban green areas. *In Conference Proceedings: 14th IWA/IAHR International Conference on Urban Drainage (pp. 35-38)*. IWA/IAHR International Conference on Urban Drainage.

Nielsen, K. (2018). Monitering af regnafstrømning fra grønne urbane arealer (Monitoring of rainfall-runoff from urban green areas). *Drift af Spildevandskomitéens Regnmålersystem – Årsnotat 2017 (pp. 39-43)*. Link: http://www.dmi.dk/fileadmin/user_upload/Rapporter/TR/2018/DMI_Report_18_3.pdf.

ENGLISH SUMMARY

Rainfall-runoff from urban pervious areas can contribute with significant quantities of runoff to urban drainage systems as these areas often constitute a relatively large part of the urban surfaces. This can have a large impact on the capacity of urban drainage systems and should therefore be implemented in the design process. However, the estimation of runoff from such areas is often uncertain with no empirical data to calibrate or validate pervious surface runoff models used in urban drainage modelling. Therefore, there is an urgent need for empirical datasets on the characteristics and variation of pervious surface runoff in urban hydrology.

It is often assumed that pervious surface runoff occurs in the form of infiltration excess overland flow in urban areas. However, this have rarely been confirmed by empirical studies. Empirical studies of pervious surface runoff are typically carried out in rural or agricultural areas and therefore do not necessarily represent the hydrology of urban pervious areas. Field studies of pervious surface runoff in rural and agricultural areas are often carried out with physical rainfall simulators used to study the runoff characteristics on a limited scale by applying a specific amount of rainfall to a pervious surface. Full-scale field experiments are also carried out although such studies seem to be rarer. Full-scale studies typically evaluate the runoff from entire catchments under natural hydrological conditions.

This study includes both a designed physical rainfall simulator and a full-scale field station to study the runoff characteristics from an urban pervious catchment on both small and large scale. The runoff characteristics of both experimental approaches are investigated in relation to rainfall types and soil-water properties such as soil water content and matric potential. Furthermore, it is investigated how traditional models in urban drainage engineering can simulate measured runoff compared to other alternative models.

In the study, it was found that the designed rainfall simulator and full-scale field station observed very different runoff processes. The full-scale experiment primarily measured subsurface throughflow under high soil water content conditions during fall and winter. On the contrary, the rainfall simulator measured infiltration excess runoff though under significantly higher rainfall intensities than those measured under natural condition with the full-scale field station. Generally, it was found that subsurface throughflow were the dominant runoff process. It was further found in the study, that alternative models such as a linear reservoir model and neural network models performed better in simulating measured runoff compared to traditional urban drainage models like the time-area and kinematic wave model.

DANSK RESUME

Ubefæstede overflader udgør typisk en stor andel af overfladerne i byen. Derfor kan regnbetinget overfladeafstrømning fra ubefæstede områder i byen potentielt bidrage med store mængder afstrømning til byens afløbssystemer. Dette kan have stor indflydelse på afløbssystemernes kapacitet, hvorfor denne type afstrømning også burde inddrages kvalitativt, når nye afløbssystemer projekteres. Kvantificering af overfladeafstrømning fra sådanne områder er dog forbundet med usikkerhed og som regel findes der ingen data til hverken kalibrering eller validering af de tilgængelige overfladeafstrømningsmodeller i afløbstekniske modeller. Af denne grund er der et presserende behov for empiriske dataset, der beskriver de karakteristika og den variation der findes i overfladeafstrømning fra ubefæstede områder i urban hydrologi.

I afløbsteknisk sammenhæng antages det som regel, at overfladeafstrømning fra ubefæstede områder foregår i form af, at den ubefæstede overflades infiltrationskapacitet overskrides. Dette er dog sjældent påvist rent empirisk i urban sammenhæng, hvorimod sådanne empiriske undersøgelser ofte er foretaget i rurale områder og i landbrugsområder. Feltundersøgelser af afstrømning fra ubefæstede rurale områder og landbrugsområder bliver ofte udført med specialdesignede fysiske regnsimulatorer, der tilfører en afgrænset jordoverflade en specifik regnmængde inden for et givet tidsinterval. Fuldskalafeltundersøgelser udføres i mindre udstrækning til at studere de naturligt forekommende hydrologiske overfladeafstrømningsprocesser på oplandsskala.

I dette projekt udvikles både en fysisk regnsimulator og et fuldskalafeltforsøg til at undersøge de afstrømningskarakteristika, der måtte være i et urbant ubefæstet område på både stor og lille skala. Disse afstrømningskarakteristika undersøges derefter i relation til andre parametre som regn og jordfysiske parametre, herunder jordens vandindhold og poretryk. Endeligt undersøges det, hvordan traditionelle modeller i afløbsteknisk sammenhæng præsterer sammenlignet med alternative modeller, der ofte anvendes til andre formål.

Brugen af den udviklede regnsimulator og fuldskalafeltforsøget viser, at disse to eksperimentelle tilgange observerer forskellige afstrømningsprocesser. På fuld skala er overfladenær afstrømning i det øvre jordlag den dominerende afstrømningstype ved høje vandindhold i jorden. I modsætning til dette måler regnsimulatoren kun overfaldeafstrømning som følge af, at jordoverfladens infiltrationskapacitet overskrides. Det kræver dog væsentligt højere regnintensiteter at opnå denne type afstrømning i forhold til de intensiteter, der blev målt under naturlige forhold på fuld skala. Generelt set er overfladenær afstrømning i topjorden den hyppigst forekommende afstrømningstype i dette projekt. Det kan yderligere konkluderes, at alternative modeller som en lineær reservoirmodel og neurale netværk er bedre til at modellere afstrømning end tid-areal metoden og den kinematiske bølgemodel.

PREFACE

This research has its offset in the wastewater industry of Denmark and is carried out in the industrial PhD-student arrangement funded by Innovation Fund Denmark. The project started in March 2016 and have finally been submitted for assessment to fulfil the PhD-degree in April 2019.

The general goal of an industrial PhD-study is by scientific research to find solutions on current problems in the commercial sector in many different scientific directions. The specific goal of this industrial PhD-study is to investigate how big the problem of rainfall-runoff from urban pervious areas is and how this can be handled in the future to increase the design quality of urban drainage systems. During the study, the PhD-student has been affiliated with both Aalborg University and the engineering consultancy firm EnviDan. Furthermore, the project has been carried out in close cooperation with the Danish water utility company Aarhus Water. This forms three important legs in this research project which are the scientific, product developing, and implementing legs.

This thesis is based on three scientific papers denoted as **Paper I**, **II**, and **III** on page VI. **Paper I** is in press while **Paper II** and **III** are waiting for a decision from editors or reviewers. The papers can be found in the "Appendices" chapter in the back of this thesis.

Research and development projects

Two industrial research projects have been carried out simultaneously to this industrial PhD-study. These are *'Monitoring of rainfall-runoff from urban pervious areas'* (in Danish: *'Monitering af Overfladeafstrømning fra Grønne Områder'* (MOGO)) and *'Monitoring of rainfall-runoff from urban pervious areas two'* (in Danish: *'Monitering af Overfladeafstrømning fra Grønne Områder To'* (MOTO)).

MOGO started in 2015 and ended in 2018 and were partially funded by *'The Foundation for Development of Technology in the Danish Water Sector'* (VTUF). The project was carried out in a partnership between Aarhus Water, Aalborg University, and EnviDan. MOGO had the primary goal to physically identify and document rainfall-runoff from urban pervious areas with an experimental approach. MOGO has been the primary contributor of funds to experimental facilities in this PhD-study.

MOTO started in 2018 and ends in 2020 and is partially funded by *'The Development and Demonstration Program in the Danish Water Sector'* (VUDP). The project is carried out in a partnership between Aarhus Water, Aalborg University, and EnviDan. The primary goal of MOTO is to elaborate on the results obtained in MOGO and bring the results to a larger scale. Furthermore, MOTO works on optimising the developed measurement facilities in MOGO to make these more available for broader use in the Danish water utility sector.

Finally, a workgroup has been established in The Danish Committee of Wastewater (Spildevandskomitéen) which collect the knowledge on runoff from pervious surfaces and develop ideas on how to include this type of runoff in the design of urban drainage systems in the future.

ACKNOWLEDGEMENTS

Before my supervisors and I applied for an Industrial PhD scholarship, I told my university supervisor, Michael, that I was very much in doubt whether I should head into a PhD-study or do something else. Michael told me, *"the problem with young people today is that they got to many opportunities – if I was offered a PhD scholarship at my time, I would go for it"*. And so, I did, and I am thankful today for my decision. The study allowed me to dig very deep into an unexplored topic in urban drainage engineering and it has given me a unique skillset which I am looking forward to applying in the future.

First, I would like to thank my supervisors, Michael and Mads, whom have been extremely inspiring throughout my PhD-study. Thank you for giving me the opportunity to make a PhD-study. Your support and guidance have been very important to me and I have learned a lot from you.

Thanks to my university colleagues Søren, Jesper, and Per for their constructive discussions and help on scientific papers throughout the study. Furthermore, thank you to my colleagues in the office at Aalborg University – Anja, Amelia, Rasmus, Lasse, and Christoffer – for a lot of fun discussions on topics of both academic and very non-academic character. Additionally, I want to express my gratitude to my industrial PhD student colleague, Anja, whom I have had a lot of constructive and supportive talks with during the last three years. I would also like to thank Anette for her help in the laboratories which is very much a foreign habitat to me.

I would also like to bring a thanks to my team manager in EnviDan, Jan, who has been really understanding throughout my study and for his help on managing my time and resources reasonably. Accordingly, I want to thank Søren Højmark for his enthusiasm and for attending in our regular knowledge sharing sessions. Furthermore, I would like to thank David for his support and putting ears to all sorts of problems that I have had. In general, I would like to express my gratitude to all my colleagues at the EnviDan office in Silkeborg for their kindness and their interest in the project.

I want to bring a special thanks to Lene Bassø from Aarhus Water for her commitment in the project which has helped aligning it, so it fits the needs in the Danish water sector.

Thank you to Mogens and Henrik from The Department of Agroecology at Aarhus University for their interest and help with some of the experimental aspects in the project.

I want to express my sincere gratitude to my family, to my wife Nadja and my sons Nor and Lui. Thank you Nadja for being my infinite source of love and support and for the sacrifices you have made so I could accomplish this PhD-study. Thank you Nor and Lui for bringing smiles on my lips every single day and for thinking that I am much cooler throwing balls and gaming PlayStation than I am doing a PhD.

I love you.

TABLE OF CONTENTS

TABLE OF FIGURES

CHAPTER 1. INTRODUCTION

Urban drainage systems have a substantial role in the sanitation of the urban environment. Separation of wastewater and humans have resulted in a tremendous decline in fatal wastewater related diseases. In developed countries, wastewater is typically collected and transported in underground sewers and is completely separated from the surface. Transportation of wastewater typically occurs in either combined or separated sewer systems (Butler et al., 2004). Combined sewer systems collect and transports both wastewater and rainfall-runoff in the same pipes while separated sewer systems transport wastewater and rainfall-runoff in separate, non-connected, pipes. Generally, separate sewer systems have been the preferred sewer type for several decades. In this way, it is avoided that diluted wastewater reaches terrain during flood and the pollution from especially combined sewer overflow is minimised (Gromaire et al., 2001).

During torrential rainfall, there is a risk that rainfall-runoff from urban areas will exceed the discharge capacity of either the combined or separated sewer systems. This could potentially result in flooding which poses a risk of either human contact with pathogenic wastewater or drowning incidents. Furthermore, flooding in the urban environment can do significant damage to buildings and objects or facilities of sentimental value. Therefore, the frequency of floods should be minimised. Specifically, in Danish urban drainage design practice, wastewater should not reach terrain more frequently than every fifth year for separated sewer systems and every tenth year for combined sewer systems (Spildevandskomitéen, 2005).

To minimise the potential risk of loss of human life and material damage during flooding, urban drainage systems must be designed using the best available knowledge and consequently develop the knowledge on topics which are not fully understood. As flooding is the result of rainfall-runoff from the surrounding catchments of the urban drainage systems, the rainfall-runoff processes in the catchments are some of the most important factors in urban drainage design where uncertainty can and should be decreased.

Rainfall-runoff is typically generated from impervious and pervious surfaces (Boyd et al., 1993; Boyd et al., 1994). Impervious surfaces are impermeable, and it is assumed that the infiltration capacity of these is zero. These surfaces are covered by different types of pavement, asphalt, buildings etc. Impervious surfaces discharge water to the drainage systems frequently and discharge is typically linearly correlated to rainfall quantities. Pervious areas discharge water because of rainfall less frequently. Pervious areas are typically covered by vegetation, soil, and gravel. In pervious areas infiltration can transport a significant amount of rainfall falling upon the surface and in that way drain the surface. Therefore, runoff from pervious surfaces only occur if the infiltration capacity of the underlaying soil is exceeded. Examples of this is seen in Figure 1.1 where runoff from two different pervious surfaces discharges rainfall to impervious areas.

Figure 1.1. *Rainfall related runoff from two pervious surfaces to impervious surfaces. Left: Runoff produced on an agricultural field flowing towards a nearby road. Right: Runoff produced from a recreational grass park in a residential area in Lystrup, Denmark.*

The infiltrating property of pervious surfaces increases the complexity in terms of estimating runoff in an urban drainage context. Compared to impervious surfaces, infiltration results in a highly non-linear relationship between rainfall and runoff generation. Thereby, runoff from pervious surface is significantly harder to quantify. Additionally, runoff from pervious surfaces have a high spatial and temporal variation, as the potential infiltration of rainfall depends on many variables such as soil texture, current soil-water conditions, and surface vegetation.

Compared to the high complexity of pervious surface runoff processes, studies on rainfall-runoff from pervious areas in the urban environment is limited in the scientific literature (Redfern et al., 2016). This often results in simplified approaches in quantifying this type of rainfall-runoff in an urban drainage engineering context. Recently though, this topic has gained increasing interest in the Danish water utility sector combined with an increased focus on extraneous water. The reason of this is situations where the percentage of runoff in the drainage systems is unlikely to be explained solely on rainfall precipitating on impervious surfaces. As the runoff coefficient in some areas is above one, this means that other sources (extraneous water) than rainfall on impervious surfaces must discharge water to the drainage systems. This is seen in some wastewater treatment plants where likely quantities of rainfall contribute with different quantities of runoff in different periods of time.

For example, extraneous water is present at Viby Renseanlæg (Viby Wastewater Treatment Plant) in Aarhus, Denmark. This is seen in Figure 1.2 where fluctuations in the discharged runoff volume at the wastewater treatment plant relative to accumulated precipitation seems to be seasonally dependent. Generally, the baseflow is highest during winter and lowest during summer. The primary reason of this is most probably infiltration into the pipes of the urban drainage network. The baseflow is represented by the lowest points along the graph in Figure 1.2. The baseflow is most probably high during fall and winter because of a higher soil water content in these seasons. This increases the water pressure on the outside of the pipes in the drainage network and forces soil-water through cracks in the pipe walls. Thereafter, infiltrated water in the pipes will eventually reach Viby Renseanlæg.

On top of the baseflow, the inlet water volume relative to rainfall varies significantly. However, it is generally seen that peaks on the graph in Figure 1.2 becomes higher more frequently during fall and winter. Furthermore, peaks seem to extend over longer periods during fall and winter. Therefore, the water volume discharged to Viby Renseanlæg is higher during fall and winter compared to the summer period. This could indicate that runoff is occurring from sources that are not related to impervious surfaces, as runoff is not expected to vary significantly from the impervious areas in the catchment of Viby Renseanlæg if the general degree of imperviousness does not increase.

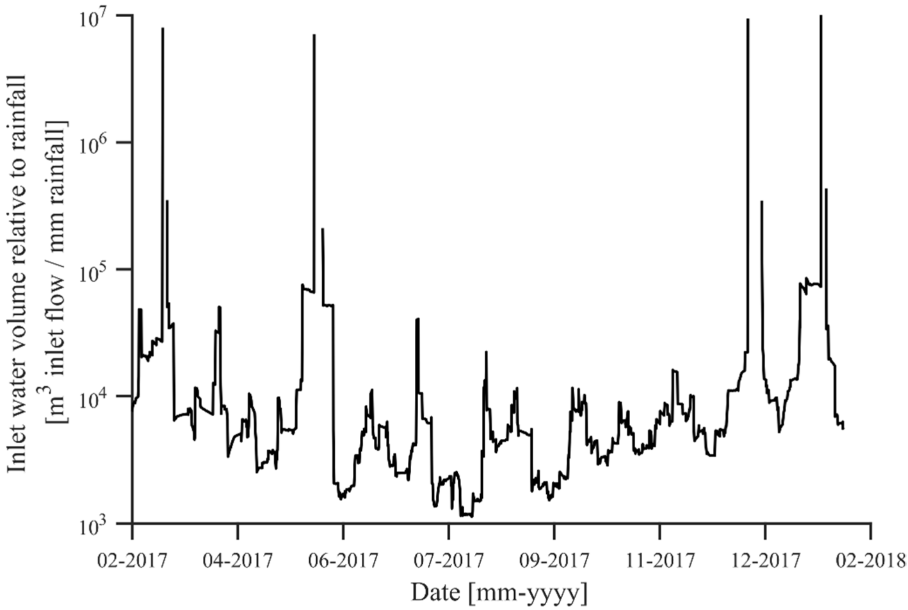

Figure 1.2. *Ten-day moving average of accumulated discharge to inlet of 'Viby Waste Water Treatment Plant' (Viby Renseanlæg) relative to accumulated rainfall measured at Viby Renseanlæg.*

High and long-term peaks during fall and winter cannot be explained solely on impervious runoff. Several sources could contribute to these periods of increased runoff. However, these are difficult to separate from a single hydrograph as presented in Figure 1.2. The primary sources that increase runoff during fall and winter are most probably due to lower evapotranspiration in these seasons. These sources could be increased infiltration through pipe leaks due to high or full saturation of the soil, and runoff directly from pervious surfaces.

In this study, the primary goal is to identify and isolate runoff from pervious surfaces. In this way, it is possible to assess the dynamics of pervious rainfall-runoff. Thus, the impact of this type of runoff in different runoff situations can be evaluated. Runoff from pervious areas can affect the urban drainage systems in different ways, whereas the general issues are:

- Unexpected sudden runoff from pervious surfaces could cause the total runoff to the drainage systems to exceed the discharge capacity of the pipes.
- Unexpected discharge to detention basins increases the time before these have been completely emptied of detained water. This could lower the storage capacity in the case of coupled rainfall events.
- Runoff from pervious surfaces which contributes to the total inlet flow at wastewater treatment plants could deteriorate the treatment efficiency as concentrated wastewater is diluted.

1.1. RAINFALL-RUNOFF MODELLING IN URBAN DRAINAGE

Rainfall-runoff from pervious areas is the result of excess rainfall that cannot percolate into the underlying soil. This can be formulated by a continuity equation for simple urban drainage models as presented in equation (1) (Nielsen et al., 2019):

$$\frac{dy}{dt} = P - \frac{Q(y)}{A} - f \tag{1}$$

Where y [m] is the water level on the pervious surface, t [s] is time, P [m s^{-1}] is rainfall intensity, Q [m^3 s^{-1}] is the runoff rate from the pervious surface, A [m^2] is the surface area of the pervious area, and f [m s^{-1}] is the infiltration rate.

Generally, the equation expresses that if the rainfall intensity is higher than the infiltration capacity, rainfall will start to pond on the permeable area. This will increase the water level on the surface and thereby initialise runoff. However, the theory and physical processes are significantly more complex than presented in equation (1).

The infiltration rate is dependent on numerous factors such as the soil texture (Groenendyk et al., 2015), the effective porosity i.e. the larger pores (macropores) in the soil (Beven and Germann, 1982; Poulsen et al., 1999), and soil compaction which can be severe in urban areas (Gregory, 2006). Furthermore, the infiltration rate is strictly correlated to the soil water content which varies in time (Campbell, 1974).

Additionally, different surface properties such as the density of grass (Pan and Shangguan, 2006) and the type of plant cover (Pan et al., 2006; Quinton et al., 1997) affects the quantity of runoff produced. In this regard, runoff generally reduces when the plant cover increases. Finally, the morphological properties of the surface have a different impact on produced runoff (Sharma, 1986).

In urban drainage modelling, many of the above-mentioned factors that can affect runoff are not included for practical reasons. Instead, the estimation of runoff from pervious surfaces is often carried out based on simplified models. In the following, the most general theories on soil-water transport and modelling of infiltration and runoff processes are described.

1.1.1. SOIL-WATER TRANSPORT MECHANISMS

Rainfall-runoff from urban pervious surfaces is strictly related to the underlaying soil and its characteristics. Soils consist of three primary components as presented in Figure 1.3. These are (i) solids, usually constituted by clay, silt, sand, and gravel that have different particle sizes, (ii) water, which either sticks to the solids or is in a free flow phase in the soil pores, and (iii) an air component, which fills out space not filled by either solids or water (Brady, N.C., 1984). In addition, most soils also contain a

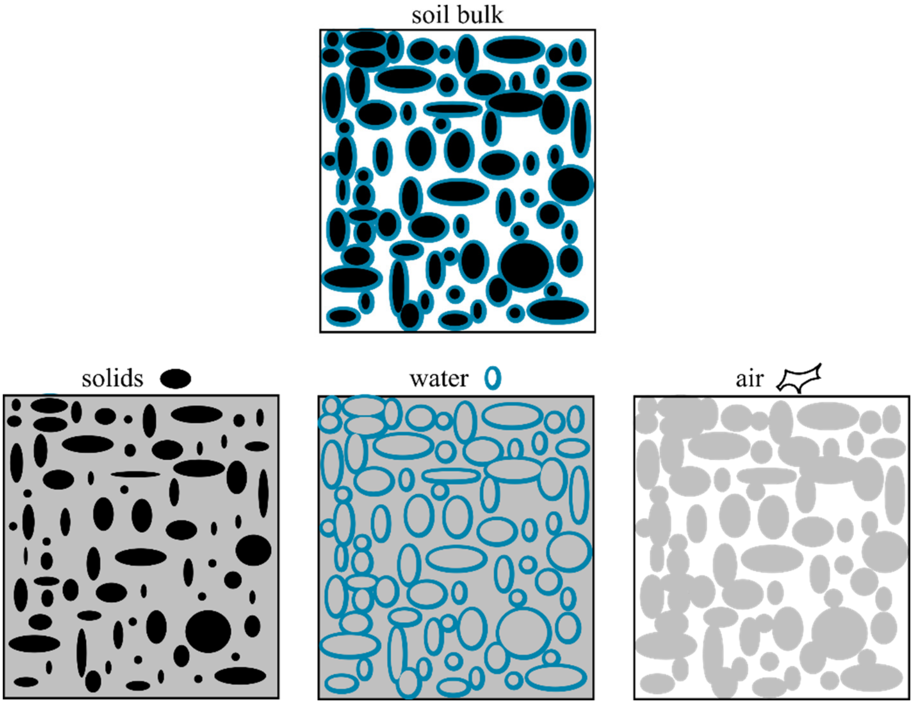

Figure 1.3. *The three components of the soil bulk. A soil typically consists of solids, water, and air.*

small amount of organic matter. Organic matter does not take up much of the volume of the soil bulk, but it can have significant effects on the infiltration in the soil as organic matter can cause water repellency of the soil (de Jonge et al., 1999).

The distribution of solid types is typically defined as the particle size distribution and is often used to classify the soil and its general properties whereas the USDA soil classification is one of the most widely used approaches (Ashman and Puri, 2013).

The volume fraction of solids typically remains constant unless the soil is exposed to some sort of physical process such as compaction or mechanical movement of the soil. The volume fractions of water and air varies depending on prior rainfall and evapotranspiration from the soil. If the water fraction increases, the air fraction decreases. The volume fraction of water in the soil bulk is referred to as the soil volumetric water content and is one of the most applied and analysed parameters in this study which affect the hydraulic conductivity of the soil (Rose et al., 1965).

The total volume of air and water in the soil bulk is referred to as the total porosity and is the maximum volume which can be filled with water. It is also within the total porosity that soil-water transport takes place. Soil-water transport in the pores is driven by the soil-water potential and gravity. The soil-water potential describes the negative pressure (suction) in soils under unsaturated conditions because of capillary and adsorptive forces. This is also referred to as the soil-water retention characteristics (Van Genuchten, 1980) and is largely dependent on the physical properties of the soil (Gupta and Larson, 1979).

The capillary force in a soil is dependent on the diameter of the soil pores. Generally, smaller pore diameters, i.e. either pores in a highly compacted soil or a soil constituted by small particles (e.g. clay), tend to have a higher capillary force. The result of this is a higher negative pressure in these soils. On contrary, soils with larger pore diameters (sand and gravel) have a lower capillary force and thereby less negative pressure within them. Adsorption is the result of adsorptive forces between soil particles and water molecules, which makes water molecules stick to the soil particles. Furthermore, water molecules which sticks to the soil particles will attract additional water molecules because of dipolar intermolecular forces within them (Brady, N.C., 1984). This results in a thin layer of water surrounding the soil particles.

The result of the soil-water potential and the size of the negative pressure is that it forces water into the soil by suction. The soil-water potential is strongly correlated to the soil water content which is the volume fraction of water per soil volume unit.

Gravitation is the second driver of water transport through the soil. As a soil becomes increasingly saturated, the soil-water potential becomes lower (i.e. the negative pressure in the soil decreases). At some level of soil water content, the gravitational pull will be as large as the negative pressure in the soil. This means that if the soil water content reaches higher levels, gravitation will force water so move vertically in the soil as the negative pressure from capillary and adsorptive forces are no longer high enough to bind water in the soil bulk. Generally, when the gravitational force is as large as the soil-water potential, the remaining air-filled pore volume fraction is called the effective porosity. This porosity fraction represents the larger pores in the soil in which the primary water transport occurs under saturated conditions in the soil (Poulsen et al., 1999).

The physics of soil-water transport is generally formulated in Richard's equation which the most applied model for soil-water transport simulation. Richard's equation is solved in numerical solution schemes (Celia et al., 1990; Van Dam and Feddes, 2000) and describes the change in soil water content in a certain soil volume as a function of the soil-water potential and gravity-driven water transport in the soil.

Generally, the lowest potential infiltration rates are found in clayey soils while the highest are found in sandy soils (Rawls et al., 1982). This generally means that the potential for infiltration is highest in areas with sandy soil. However, local soil physical properties could affect this such as the effective porosity which are well correlated with the saturated hydraulic conductivity, K_s (Poulsen et al., 1999).

1.1.2. INFILTRATION MODELLING IN URBAN DRAINAGE

Infiltration models used in urban drainage modelling are typically simplified models either empirically derived based on measurements or simplifications of Richard's infiltration equation. Numerous infiltration models exist; however, two infiltration models have found wide application in urban drainage engineering. These are Horton's infiltration equation and the Green-Ampt model (R. E. Horton, 1933; R. E. Horton, 1939; Green and Ampt, 1911). The general assumption of these infiltration models is that infiltration propagates vertically into the soil. Furthermore, all infiltration models describe that the infiltration rate decays as the soil becomes increasingly wet.

Horton's infiltration equation

Horton's infiltration equation is solely based on empirical observations and estimates the infiltration capacity of the surface as a function of time (R. E. Horton, 1939):

$$f(t) = f_c + (f_0 - f_c)e^{-kt} \tag{2}$$

Where f [m s^{-1}] is the infiltration rate, f_c [m s^{-1}] is the saturated infiltration capacity, f_0 [m s^{-1}] is the initial infiltration capacity, and k [s^{-1}] is the decay constant of infiltration.

Equation (2) describes the infiltration capacity decreasing from an initial value, f_0, to a final infiltration capacity, f_c. The infiltration capacity decreases at the function of time and a decay constant, k.

The Green-Ampt infiltration model

The Green-Ampt model is physically based and derived on a simplification of Richard's equation. The Green-Ampt model presented in equation (3) assume that the soil is homogenous and that water movement into the soil occurs with a sharp wetting front (Green and Ampt, 1911; Mein and Larson, 1973):

$$f(t) = K_s \left(1 + \frac{y_0 + \psi_{wf}}{Z}\right) \tag{3}$$

Where K_s [m s^{-1}] is the saturated hydraulic conductivity, y_0 [m H_2O] is the water level of ponding water on the soil surface, ψ_{wf} [m H_2O] is the soil-water potential at the wetting front, and Z [m H_2O] is the distance from the soil surface to the wetting front.

The Green-Ampt model assumes that the soil water potential at the wetting front is constant and that the wetted zone of depth Z is uniformly saturated (Kale and Sahoo, 2011). The distance from the soil surface to the wetting front, Z, is calculated by (Mein and Larson, 1973):

$$Z = \frac{F}{\Delta\theta} \tag{4}$$

Where F [m] is the cumulative infiltration depth and $\Delta\theta$ [m^3 soil / m^3 H_2O] is the initial soil volumetric water content deficit, which is the difference between the saturated soil volumetric water content, θ_s [m^3 soil / m^3 H_2O], and the initial soil volumetric water content θ_i [m^3 soil / m^3 H_2O].

1.1.3. SURFACE RUNOFF MODELLING IN URBAN DRAINAGE

Surface runoff models used in urban drainage varies from two-dimensional models to simplified empirical or semi empirical one-dimensional models. The general formulation of surface runoff is the physically based Saint-Venant equations for two-dimensional flow (Tayfur et al., 1993). The numerical solution of the Saint-Venant equations is typically used for modelling of overland flow in commercial models such as MIKE 21 (DHI, 2017a). However, simplified overland flow models are often used to estimate the surface runoff in pipe flow models of urban drainage networks such as MIKE URBAN (DHI, 2017b). In this way, the computational effort needed is minimised.

Kinematic wave model

One widely applied model is the is the kinematic wave model for one-dimensional which is a simplification of the St. Venant equations (Butler et al., 2004). The kinematic wave model is based on the continuity equation in equation (1) and Manning's formula for uniform flow in open channels presented in equation (5) (Munoz-Carpena et al., 1999).

$$Q(t) = BMy(t)^{\frac{5}{3}} I^{\frac{1}{2}} \tag{5}$$

Where B [m] is the width of the flow channel, M [$m^{1/3}$ s^{-1}] is Manning's number, y [m] is the water level in the flow channel, and I [m m^{-1}] is the slope of the surface of the flow channel.

The kinematic wave model is derived by combining equation (1) and (5) as presented in the differential equation below:

$$\frac{dy}{dt} = P - \frac{BMy(t)^{\frac{5}{3}} I^{\frac{1}{2}}}{A} - f \tag{6}$$

The differential equation can be solved in a numerical solution scheme as seen in equation (7) using an explicit finite difference scheme:

$$\frac{y_{n+1} - y_n}{\Delta t} = P_n - \frac{BMy_n^{\frac{5}{3}} I^{\frac{1}{2}}}{A} - f_n \tag{7}$$

Where n [-] is the time discretisation and Δt [s] is the time increment.

Time-area model

The time-area method is a fully empirical approach to surface runoff modelling where runoff is calculated as a function of time (Butler et al., 2004):

$$Q(t) = \sum_{n=1}^{N} \Delta A_j i_n \varphi \tag{8}$$

Where i_n [m s^{-1}] is the rainfall intensity, ΔA_j [m^2] is the contributing area to runoff, φ [-] is the runoff coefficient, n is the time increment, and j is the increment of change in the runoff contributing area.

Due to the simplicity of the time-area model, it is also the most frequently used model in Danish engineering practice for runoff estimation in pipe flow models such MIKE URBAN (DHI, 2017b).

1.2. FIELD STUDIES FOR INVESTIGATION OF PERVIOUS SURFACE RUNOFF PROPERTIES

Field studies are often carried out as very few data are available to evaluate the accuracy of applied models. Furthermore, some physical processes are hard to quantify and therefore field studies seem more practical in these cases. Field studies on rainfall-runoff from pervious surfaces can be divided into two categories whereas the first is full scale field studies which study runoff on catchment sized scale. The second type of field study is physical rainfall simulator studies which are typically carried out on a few square meters.

1.2.1. PHYSICAL RAINFALL SIMULATION

The overall goal of a physical rainfall simulator is to produce an often very specific type of rainfall. By irrigating rainfall onto a limited surface area with a certain amount of rainfall, different physical processes can be studied. Some of the frequently studied parameters are processes like runoff generation, hydrophobicity of the surface, soil erosion, and nutrient transport (Burch et al., 1989; Arnaez et al., 2007; Sharpley, 2003).

Physical rainfall simulators have been designed for at large variety of purposes. However, most rainfall simulators have some common features. In general, portable rainfall simulator irrigates rainfall on the soil surface with either spraying nozzles or dripping (Bowyer-Bower and Burt, 1989). The use of spraying nozzle requires a pressurized system where the spraying nozzles are supplied with water by a pump. This method is widely used as it is relatively easy to apply because pressure is usually the only parameter to control. Furthermore, spraying nozzle simulators can also irrigate rainfall towards a larger surface area (Humphry, 2002; Benavides Solorio and MacDonald, 2001; Cerdà et al., 1997). Drop forming simulators are driven by gravitation where small perforations lets water pass and drip towards an area of interest (Clarke and Walsh, 2007).

Portable rainfall simulators are typically used for field studies to investigate in-situ properties of a specific soil and soil surface. However, the techniques are also used in laboratories under more controlled conditions in terms of e.g. soil-water content and surface slope (Lora et al., 2016; Römkens et al., 2002).

Rainfall simulators are typically designed towards optimal performance on specific performance parameters such as uniform distribution of raindrops and the kinetic energy of raindrops (Abudi et al., 2012; Christiansen, 1942; Gilley and Finkner, 1985; Iserloh et al., 2013; Van Dijk et al., 2002).

Few attempts have been made to design portable rainfall simulators that can simulate a larger spectrum of rainfall intensity. The reason is, that most rainfall simulators are designed to produce one specific rainfall intensity. This can be problematic as this requires several simulators to evaluate e.g. runoff behaviour under different types of rainfall. Instead of using several simulators for different rainfall intensities, Miller (1987) investigated how solenoid valves could be implemented to generate control strategies the applied rainfall to produce different rainfall intensities with the same simulator. Miller (1987) showed that by opening and closing the solenoid valve at different frequencies, it was possible to generate different rainfall intensities with the same simulator. The use of solenoid valves to control rainfall simulators was further studied by Paige (2004) who developed a computer-controlled system. In this way, Paige (2004) could change the intensity during simulation if needed, though through manual intervention.

Most rainfall simulators are designed for studies in rural and agricultural areas and little focus have been brought to the urban environment on this topic. However, recent investigations by Yakubu and Yusop (2017) have studied rainfall simulators from other research fields and evaluated their adaptability for rainfall simulation on urban impervious surfaces.

The general pitfall of rainfall simulators is that rainfall-runoff is measured on a relatively small scale. This can be a problem due to the heterogeneity of soil but also on how measurement results can be extrapolated to larger scales. Furthermore, the primary type of runoff that is studied with rainfall simulators are infiltration excess overland flow. This could lead to a misinterpretation of the hydrological behaviour in some catchments.

1.2.2. FULL-SCALE EXPERIMENTS

Full-scale experiments are carried out on varying catchment sizes and can be as large as several square kilometres. The advantage of full-scale experiments is that they evaluate the general hydrology of entire catchments, whereas rainfall simulators only measure the hydrological conditions on a very small sub-part of the respective catchments.

Full-scale experiments are to a large degree dependent on natural meteorological and hydrological conditions, and do therefore also operate under some degree of randomness in terms of rainfall patterns, dry weather periods, antecedent soil water content etc. However, successful full-scale studies can supply important information on the hydrological behaviour of catchments and on how the current theoretical understanding should be translated in the field.

Full-scale studies approach very different issues and only few focuses directly on surface runoff from pervious surfaces. Some studies investigate how measured soil water content in watersheds can be used to predict watershed runoff. For example, Jacobs et al. (2003) studied how remotely sensed soil water content in a watershed could be used to optimize runoff estimate. Additionally, Grayson (1997) investigated how spatial soil moisture patterns could be used to predict if soil-water is vertically infiltrating or whether horizontal water transport was present in the soil.

Generally, full-scale studies focused directly on surface runoff types from pervious surfaces are very limited. Especially in urban drainage where such studies barely exist

(Redfern et al., 2016). However, some full-scale studies have been carried out in rural areas. Dunne and Black (1970a) and Dunne and Black (1970b) investigated runoff in an experimental watershed. They found that runoff primarily occurred from rainfall precipitating on saturated spots where rainfall could not infiltrate and therefore would run off the surface. Additionally, Dunne and Black (1970a) also found that subsurface throughflow was present. Dunne and Black (1970a) found no evidence of infiltration excess runoff as presented by R. E. Horton (1939). Kirkby and Chorley (1967) did similar findings that subsurface throughflow is the dominating runoff type. Kirkby and Chorley (1967) further concluded that infiltration excess runoff is just one end-member of several runoff types. Pilgrim et al. (1978) found that that three types of runoff contributed to runoff in general. These were (i) infiltration excess overland flow, (ii) saturation excess overland flow, and (iii) subsurface throughflow. These are also the three surface runoff processes that are potential contributors to runoff during rainfall. Although these processes are primarily observed and documented in literature in rural areas, they could also all be potential contributors to runoff from urban pervious areas. The characteristics of these three runoff processes are briefly summarized below:

(i) Infiltration excess overland flow is produced when the rainfall intensity exceeds the infiltration capacity of a permeable surface. The excess rainfall will thereby pond on the surface and eventually start to discharge from the surface. The infiltration capacity is often estimated based on the infiltration theory of R. E. Horton (1939) and Green and Ampt (1911). This type of runoff occurs on the soil surface.

(ii) Saturation excess overland flow is produced if the soil beneath a surface is fully saturated as shown by Dunne and Black (1970a). In this way, there is practically no vertical infiltration and all rainfall will thereby pond on the surface and finally discharge. This is often seen if a ground water table temporarily reaches the soil surface.

(iii) Subsurface throughflow is different from infiltration and saturation excess overland flow. This type of runoff occurs in the soil matrix by horizontal water transport. Horizontal water transport in the soil is initiated as the storage capacity of the soil is exceeded. Therefore, the soil water content must have exceeded some critical level as Kirkby and Chorley (1967) presented in their study.

As studies indicate, rainfall-runoff, at least in rural areas seem to consist of different and separated processes. This could also be the case in urban pervious areas as the soil physics most probably will not vary much. Even at Horton’s experimental laboratory, infiltration excess overland flow does not seem to have been the only contributor to runoff as Horton’s overland flow theories could indicate. Beven (2004) conducted a review of Horton’s studies and found that there are indications that subsurface throughflow could have been a significant contributor to runoff in the Horton’s experiments.

1.3. RESEARCH QUESTIONS

In current urban drainage design practice, runoff from pervious areas is often neglected or given little attention in terms of the quality of applied models. Furthermore, the approach to pervious surface runoff in urban drainage is highly focused on infiltration excess overland flow. However, this approach seems to be one-sided according to experimental studies from rural areas. According to these studies, rainfall-runoff processes should be divided into three main categories which are (i) infiltration excess overland flow, (ii) saturation excess overland flow, and (iii) subsurface throughflow. The ***aim and scope*** of this study is to investigate if rainfall-runoff processes in the urban landscape is like those of studies in rural areas and how rainfall-runoff can be monitored in the urban landscape. Additionally, it is the aim to find key parameters which are good indicators of surface runoff and how these can be implemented in current urban drainage modelling practice. This led to the following general research question with a set of associated sub-questions:

What identifies an urban pervious area that have a high risk of producing rainfall-runoff?

Sub-question I: How is rainfall-runoff from urban pervious areas physically quantified?

Sub-question II: How frequently does urban pervious surface runoff occur?

Sub-question III: How do physical rainfall simulators perform in estimating the risk of rainfall-runoff from urban pervious areas?

Sub-question IV: What is the dominant rainfall-runoff processes from urban pervious areas?

Sub-question V: What are the most important soil parameters in term of indicating rainfall-runoff from an urban pervious area?

Sub-question VI: How do currently applied surface runoff models agree with measured surface runoff from an urban pervious area?

CHAPTER 2. METHODOLOGY

This study is primarily based on empirical methods to observe and quantify rainfall-runoff. In this way, through measurements, it is investigated if it is possible to evaluate and enhance current assumptions on rainfall-runoff from pervious surfaces in urban drainage engineering. Two experimental setups are developed and applied on the experimental catchment seen in Figure 2.1. Full-scale observations are used to evaluate currently applied models and their applicability to reproduce measured runoff.

Figure 2.1. *Experimental location in Lystrup, Denmark.*

2.1. EXPERIMENTAL SITE

The experimental site is located in Lystrup, Denmark. The surface is grass covered and is a recreational green area that can potentially discharge rainfall to a sidewalk and road downstream. The area is seen in Figure 2.2 and covers 4,300 m^2. One of the experimental setups collects runoff from the entire area, while the other, a rainfall simulator-based study, measures runoff from one square meter areas at different locations on the hill. The hill has an average slope of 8.8 %. The topsoil in Lystrup is characterized as a sandy loam according to the USDA soil classification system

(Ashman and Puri, 2013) and have a saturated hydraulic conductivity of 1.14 mm min^{-1}. Furthermore, the total and effective porosity in 10 cm of depth has been measured to 0.43 and 0.18 respectively with intact samples and retention box measurements as seen in Figure 2.3. Lastly, an organic matter content of 5.06 % was found in the topsoil.

In approximately 46 cm of depth, a layer transition was found to a layer with a slightly higher silt and clay content, though still a sandy loam. The organic matter content in

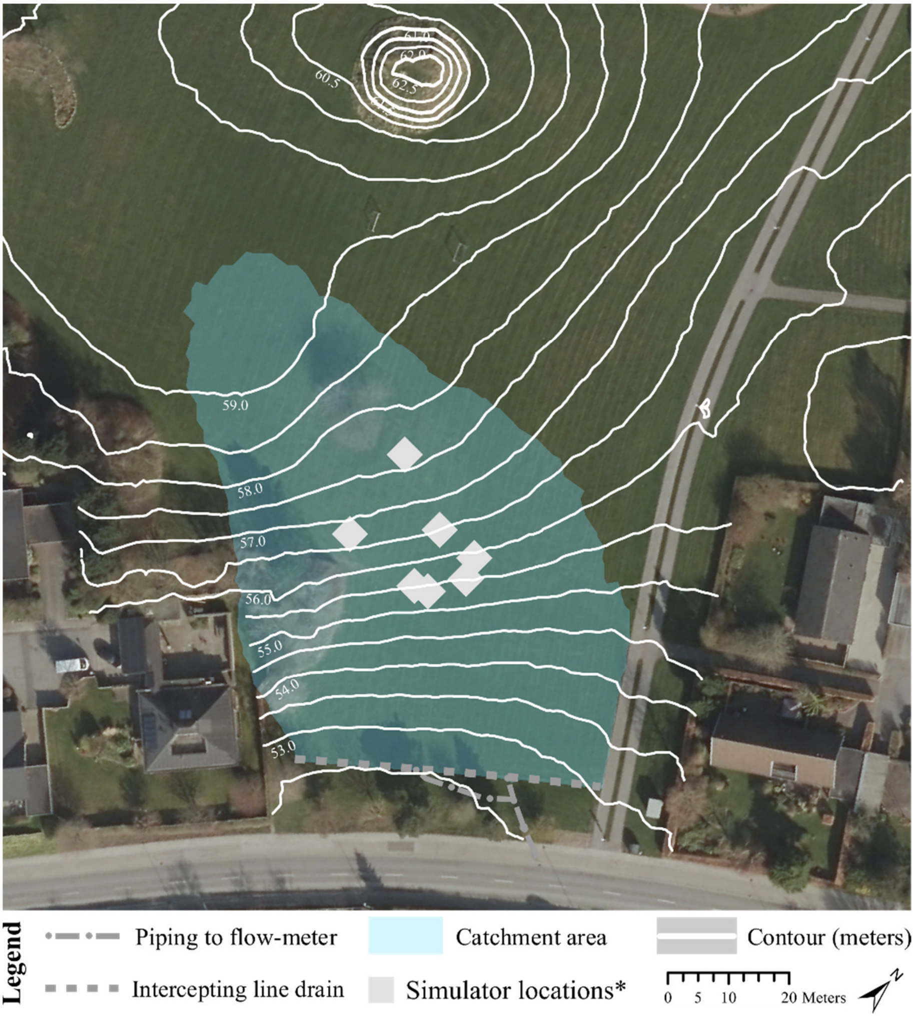

Figure 2.2. *Overview of the experimental catchment in Lystrup, Denmark. Intercepting line drain and flow-meter indicated on the figure are used for full-scale experiments. *Approximate location of physical rainfall simulations.*

this depth was 1.34 %. The experimental procedures to investigate the above-mentioned soil properties are thoroughly explained in **Paper I.**

Figure 2.3. *Left: Retention box for analysis of intact samples. Right: Intact sample of soil with a live earthworm.*

Active rainfall-runoff from the experimental location have been visually observed several times during the field study. One occurrence is seen in Figure 2.4 where runoff is present. Rainfall is discharged from the grass covered area to the sidewalk and road and thereby to the drainage system although the surrounding impervious areas are completely dry.

Figure 2.4. *Active rainfall-runoff from the experimental location. Discharge occurs although the impervious surfaces are dry.*

2.2. FULL-SCALE MONITORING OF RAINFALL-RUNOFF

A full-scale monitoring system was established at the experimental site in June 2016. The monitoring system collects rainfall-runoff from the 4,300 m^2 catchment under natural conditions. In this way, it is possible to observe how runoff responds under e.g. different levels of soil water content and different types of rainfall. This will provide a natural reference point to portable rainfall simulator studies which study rainfall-runoff on a limited area with artificial rainfall.

The monitoring system consist of three primary parts which are (i) a runoff monitoring system to collect and measure the rainfall-runoff rate from the area, (ii) soil sensor clusters to observe the basic soil-water conditions both in active and inactive periods of runoff, and (iii) a rain gauge to continuously measure rainfall.

2.2.1. RUNOFF MONITORING SYSTEM

The runoff monitoring system collects runoff in a 51 meter long ACO hexaline line drain (ACO Nordic, 2014) that is typically used to drain driveways and similar paved surfaces. The line drain comes in one-meter pieces and is assembled on site as seen in Figure 2.5. All joints are sealed with a special adhesive to avoid leaks. The line drain is installed in a layer of concrete to stabilise and reinforce the line drain. In March 2017, the line drain was re-established due to errors in the first installation which resulted in leakages.

Collected runoff from the line drain is subsequently transported through two outlets seen in Figure 2.6 via pipes to a grit chamber. The grit chamber removes particles, leaves and other solids that can disturb runoff measurement.

Figure 2.5. *Assembling of line drain at the experimental area.*

Figure 2.6. *Left: Outlet from line drain to the grit chamber. Right: Grit chamber. Two inlets are seen at the bottom of the picture and one outlet towards the flow-meter at the top.*

The flow rate of collected runoff is measured with a flow-meter with a calibrated Q-h relation. The flow-meter is based on a V-notch weir as seen in Figure 2.7. In this way, it is possible to measure both small and high flow rates with a relatively good accuracy. The reason for this is that there are higher variations in the water level for small flows due to the smaller cross-sectional areas in the weir.

Figure 2.7. *Flow-meter manhole with a V-notch weir.*

The water level in the weir is measured every five minutes with two Campbell Scientific CS451 pressure transducers (Campbell Scientific, 2014). Data is stored on an YDOC ML-315ADS-Li data logger (YDOC, 2016) which uploads data to an ftp-server continuously through a mobile broadband connection. As runoff is leaving the V-notch weir, the water is finally discharged to the drainage system.

2.2.2. SOIL SENSOR CLUSTERS

To investigate how the soil water respond to rainfall and how soil water content is related to runoff, three soil sensor clusters were established at the experimental location in Lystrup. Each soil sensor cluster was set up with four sensors each whereas the distribution of those is presented in **Paper I**.

The sensors used in this study are matric potential sensors and soil volumetric water content sensors. The matric potential sensor used are Stevens TensioMark and Decagon MPS6 sensors (Stevens, 2014; Decagon Devices, 2015). The soil water content sensors applied are the time domain reflectometry sensors Decagon 5TE-sensors and a Sentek SDI-12 Drill & Drop Probe (Decagon Devices, 2016; Sentek, 2015; Topp et al., 1980).

In Figure 2.8, parts of an established soil sensor cluster are seen. A vertically buried Ø200 pipe is used to contain a data logger that stores collected data. All equipment is buried to minimise attention gained from trespassers in the city. Sensors are wired through the pipe wall and the soil and is mounted with a few meters proximity from the pipe. Generally, sensors were installed in approximately 10 cm of depth to measure the soil-water properties close to the surface and to still avoid the dense root

Figure 2.8. *Parts of a soil sensor cluster. On the left, a vertically burried Ø200 contains the data logger to collect all data from installed sensor. On the right, a mounted Decagon 5TE soil volumetric water content sensor is seen.*

net of the grass. Measuring the soil-water content in the root net should be avoided as a relatively high soil water content can be present in the plant roots. Holes that were dug to install the sensors are afterwards filled with a slurry mix of the local soil and water.

2.2.3. RAIN GAUGE

Rainfall at the experimental location was initially measured on site (see Figure 2.9) with a triple headed rain gauge consisting of three ARG100 tipping bucket rain gauges measuring 0.2 mm tip^{-1} (Campbell Scientific, 2010). Three rain gauges are applied to increase measuring certainty and for error detection internally on the three rain gauges.

Figure 2.9. *Left: Original location of rain gauge on the experimental site. Right: New location of the rain gauge on a private property after vandalism.*

In June 2017, the rain gauge was vandalised as seen in Figure 2.10 and therefore broken on its original location at the experimental site. Therefore, it was necessary to repair it and move it to a new location. The rain gauge was re-established on a private property 400 meters away from the experimental site as seen in Figure 2.9.

Figure 2.10. *Broken rain gauge after vandlism in June 2017.*

2.3. DESIGNING A PHYSICAL RAINFALL SIMULATOR

Measuring rainfall-runoff on full-scale under natural conditions is time consuming and is also unpredictable in terms of results. Therefore, a portable physical rainfall simulator was developed to investigate the relationship between infiltration and runoff at the experimental site. In this way, it is possible to study runoff caused by predefined rainfall types, though on a smaller catchment. The rainfall simulator was developed to assess its potential use for parameterization and runoff estimation in urban drainage design. The designed rainfall simulator setup consists of two primary parts as illustrated in Figure 2.11(a)-(b). The first part is the actual rainfall simulator that is

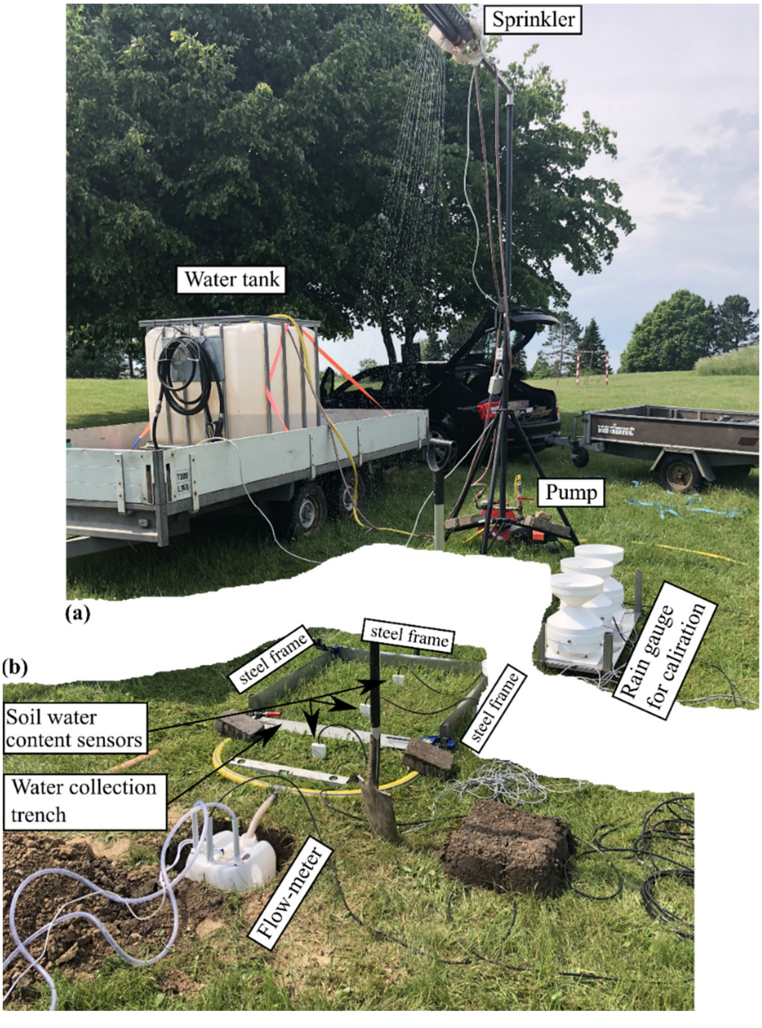

Figure 2.11. *Field use of (a) the developed portable rainfall simulator and (b) the runoff collection system presented in Paper II (Nielsen et al., "Automated physical rainfall simulator for variable rainfall on urban green areas", submitted).*

dozing and sprinkling artificial rainfall on a pervious area of interest. The second part is the runoff collection system that measures produced runoff if the infiltration capacity of the pervious surface is exceeded by the simulated rainfall. The runoff collection system collects runoff from a limited area and continuously measures the runoff rate.

2.3.1. RAINFALL SIMULATOR SPRINKLER

The rainfall simulator in Figure 2.11(a) was designed to be able to produce a wide range of rainfall intensities with just one sprinkler and pump. This is similar to the studies by Miller (1987) and Paige (2004). However, in this study, the rainfall simulator is designed to be fully controlled by a microcomputer without any need for manual intervention if the rainfall intensity must be adjusted within an event.

The developed rainfall simulator is supplied with water with a pump connected to a water tank as seen in Figure 2.11. While the pump runs on a constant rate, two solenoid valves are used to control the inflow to the sprinkler and thereby how much artificial rainfall is produced. As seen in Figure 2.12, the two solenoid valves consist of one inlet valve and one bypass valve. The inlet valve controls the amount of water that flows into the sprinkler. On contrary, the bypass valve bypasses water and leads it back towards the water tank when the inlet valve is closed. This is a necessary means for optimal operation of the valves as they need to be pressurised to remain closed.

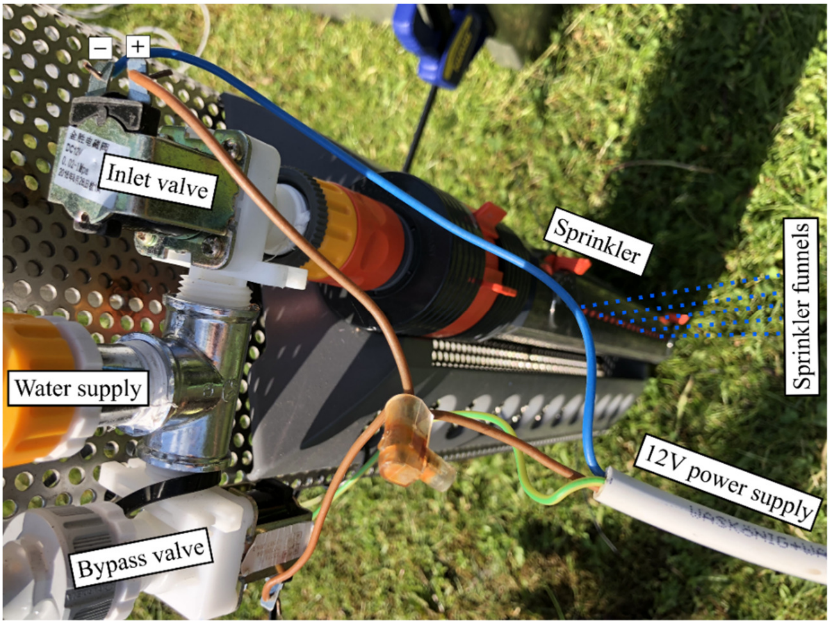

Figure 2.12. *Components of the rainfall simulator sprinkler.*

The rainfall simulator performance was tested in terms of the spatial distribution of rainfall on a one square meter measurement plot, the ability to replicate historical rainfall events, and the characteristics of raindrops compared to natural raindrops. It was found that the developed rainfall simulator has a good performance compared to other rainfall simulators in literature. Details on the developed control strategy and performance tests of the rainfall simulator are described in **Paper II** (Nielsen et al., "Automated physical rainfall simulator for variable rainfall on urban green areas", submitted).

2.3.2. RUNOFF COLLECTION SYSTEM

Runoff that is eventually produced as the rainfall intensity of the rainfall simulator sprinkler exceeds the infiltration capacity of the soil, is collected in a runoff collection system. Runoff is collected from a one square meter area (1 × 1 m). The area is limited by a steel frame on three sides and a water collection trench on the downstream side collecting runoff as seen in Figure 2.13. Collected runoff is transported through pipes to a container used as a flow-meter. The water level in the container is monitored with a Campbell Scientific CS451 pressure transducer (Campbell Scientific, 2014). Change in volume over time is thereby translated to flow. If the runoff container becomes full during simulation, two 12V pumps are used to empty the container. The soil water content is measured simultaneously in the soil beneath the studied surface area by

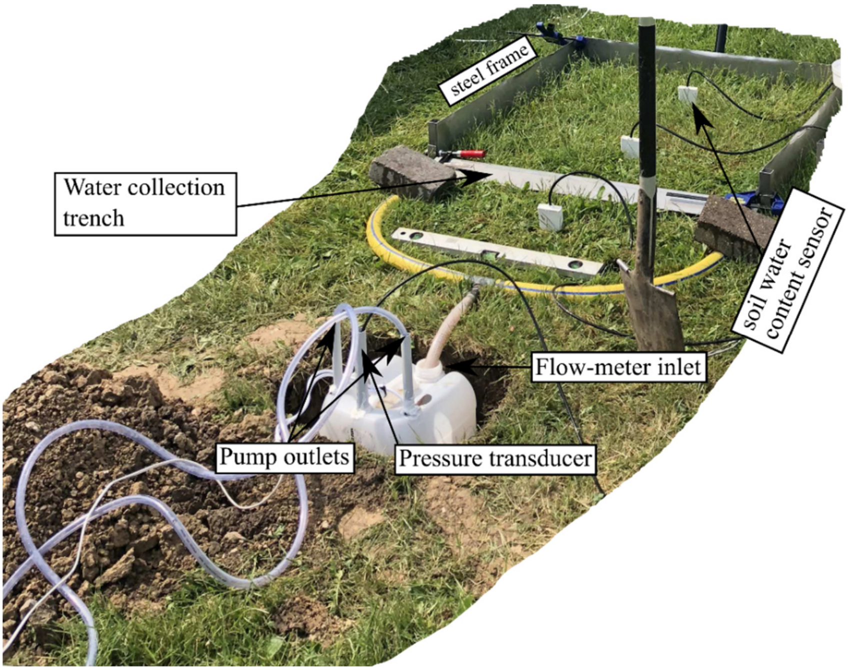

Figure 2.13. *Designed runoff collection system to monitor produced runoff.*

three Campbell Scientific CS655 soil volumetric water content sensors (Campbell Scientific, 2018).

2.4. MODELLING OF RAINFALL-RUNOFF

Traditional urban drainage models are evaluated and compared to three alternative models. These are the time-area and kinematic wave model which are typically applied in urban drainage, and regression models, a linear reservoir model, and neural network models which often have other areas of application. The models are described in detail in **Paper III** (Nielsen et al., "Modelling of subsurface throughflow in urban pervious areas", submitted) and presented with a brief description below:

- The time-area model is a fully empirical model frequently used in commercial urban drainage models for simulation of one-dimensional surface runoff. In general, this is the most widely applied surface runoff model by urban drainage engineers in Denmark for urban drainage network modelling.
- The kinematic wave model is a semi-empirical model derived from the continuity equation and a hydrodynamic flow module. The kinematic wave model is typically available in commercial urban drainage models for simulation of one-dimensional flow from catchments.
- The linear reservoir model is a semi-empirical model which is also based on the continuity equation. In this case, the hydrodynamic flow module expresses that runoff is linearly correlated to the water level in the reservoir. Linear reservoir models have many applications and are generally used in hydrologic systems where retention and storage of water occurs.
- The regression-based models are fully empirical and assume that runoff is directly correlated to the soil water content. This is an approach that have been used to simulate runoff from subsurface throughflow to e.g. rivers.
- Neural network models are mathematical models and are fully empirical without any physical terms included. The models utilize input data (in this case soil water content, matric potential, and rainfall) to quantify a given target value (in this case primarily the subsurface throughflow runoff rate). The applications of neural networks are potentially unlimited. However, it must be noted that neural network models do not explicitly reflect any physical meaning.

The models are calibrated and evaluated based on measured data collected from the full-scale field station presented in **Paper I**. The models are compared based on three performance parameters which are the root mean square error, Nash-Sutcliffe efficiency, and empirical likelihood between modelled and measured data (Ritter and Muñoz-Carpena, 2013; Nash and Sutcliffe, 1970; K. Beven and Freer, 2001; Freer et al., 1996).

CHAPTER 3. RESEARCH OUTCOMES

The research questions raised in this PhD-study is answered through an extensive field campaign applying both large- and small-scale experimental techniques to investigate the inherent rainfall-runoff processes in an urban pervious area situated in Lystrup, Denmark. The ability of traditional urban drainage runoff models to simulate rainfall-runoff is compared to other alternatives found in literature. This have resulted in research outcomes of both scientific and commercial value.

3.1. SCIENTIFIC OUTCOMES

Rainfall-runoff was monitored from a 4,300 m^2 catchment as presented in **Paper I**. The full-scale study agrees with other full-scale studies carried out in rural areas (Dunne and Black, 1970a; Dunne and Black, 1970b; Kirkby and Chorley, 1967) that subsurface throughflow and saturation excess overland flow seems to be the dominant runoff processes while infiltration excess runoff is completely absent. The field study found that subsurface throughflow occurs frequently during fall and winter, while no runoff was detected throughout summer. Furthermore, high soil water content conditions (above 0.34 m^3 H_2O / m^3 soil) must be present for subsurface throughflow to occur. Finally, measured accumulated runoff was found to be linearly correlated to accumulated rainfall.

The identification of subsurface throughflow as the primary contributor of runoff from a full-scale catchment is an important finding in this PhD-study and for Danish urban design practice as well. This contradicts the simplified assumptions of ideal soils as presented in Figure 3.1 that is often used in urban drainage engineering. The ideal soil

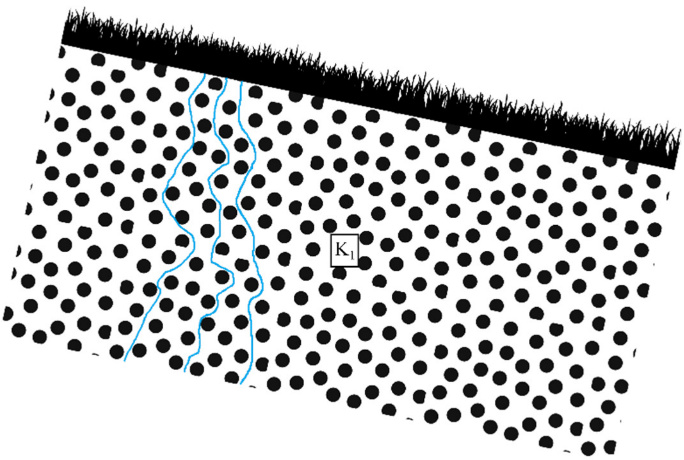

Figure 3.1. *The ideal soil and surface composition with homogenous soil structure, hydraulic conductivity, and surface slope. K_1 is the hydraulic conductivity of the soil.*

is homogenous and have identical soil-water properties with depth and it is generally assumed that infiltration propagates vertically. However, this is far from the case at the Lystrup catchment and making such assumptions for the area would be critical to the estimation of runoff production.

Soil characterization of the Lystrup catchment carried out in **Paper I** shows that the soil becomes siltier with depth. In this way, the hydraulic conductivity is most probably lower in approximately 46 cm of depth. This could cause a barrier to vertical water transport if rainfall accumulated in the upper layer over some time exceeds the hydraulic conductivity of the lower layer. The result of this is a topsoil layer that acts as a reservoir that can store water until the storage capacity is exceeded. If the storage capacity is exceeded, soil-water will start to move freely in a horizontal direction as illustrated in Figure 3.2. Generally, the storage capacity seems to be exceeded at soil water contents above 0.34 m^3 H_2O / m^3 soil.

Horizontal water movement will start when accumulated water in the upper layer can no longer be detained by capillary and adsorptive forces (suctional forces) resulting in a gravitational pull on the water that is higher than the suctional forces. In this way, water is mobilised in the soil and water transport in the direction of the slope will start and be active until the soil water content falls to a level where the adsorptive and capillary forces can bind the accumulated water in the soil pores of the upper soil layer again. This scenario is possible if the storage capacity of the entire topsoil layer is exceeded. Such levels of saturation are seen during fall and winter in Lystrup where evapotranspiration is low, and the accumulated rainfall volume is relatively high resulting in subsurface throughflow. Subsurface throughflow and thereby urban pervious runoff was observed at least on a yearly basis at the Lystrup catchment.

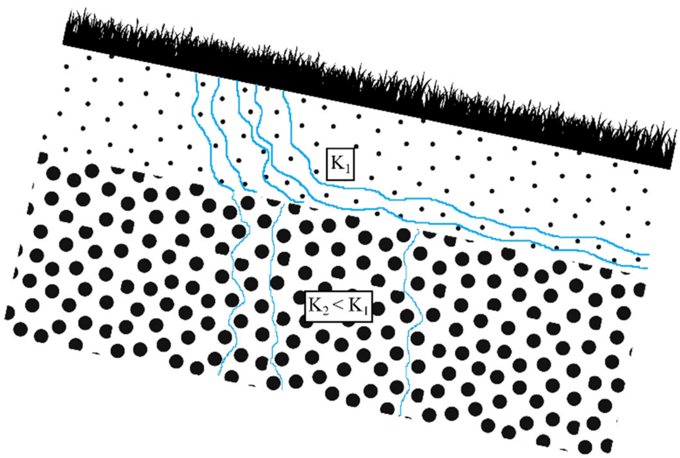

Figure 3.2. *Non-homogeneus soil with changing hydraulic conductivity with depth.* K_1 *and* K_2 *are the hydraulic conductivities of the upper and lower soil layer respectively.*

Besides subsurface throughflow as a primary runoff type on full scale, saturation excess runoff was observed as a secondary runoff process. Saturation excess runoff is mainly a derived effect of subsurface throughflow. The reason for this is that at the areas where subsurface throughflow exfiltrates from the soil onto the soil surface, there is a state of full saturation in the soil with no remaining infiltration capacity. The result of rainfall precipitating directly on these surfaces is an immediate runoff which result in some larger peak runoff rates during rainfall. Generally, saturation excess runoff resulted in the highest measured runoff rates. However, the runoff volume of saturation excess runoff is negligible compared to the runoff volume produced as a result of subsurface throughflow.

Subsurface throughflow and saturation excess runoff only occurred during fall and winter. No runoff was naturally measured under dry soil-water conditions during summer. However, the designed physical rainfall simulator in **Paper II** found that it was possible to obtain very different runoff characteristics under low soil water content conditions during summer. Rainfall-runoff experiments conducted with the rainfall simulator in this period resulted in infiltration excess overland flow. However, to produce infiltration excess runoff with the rainfall simulator during summer, a significantly higher rainfall intensity was required than those naturally recorded at the field station in **Paper I**. The reason of this must be found in the seasonal variations of soil water content conditions and its impact on the water storage of the soil.

During summer, the soil water content of the top soil layer is significantly lower which results in a higher potential water storage capacity of the soil. This results in an excess storage capacity to store water where capillary and adsorptive forces can bind water in the soil pores as the suctional forces are stronger than the gravitational forces. This have a significant influence on the results of the rainfall simulation campaign carried out in **Paper II**.

When simulating rainfall on a one square meter surface as illustrated in Figure 3.3 under low soil water content conditions, there is plenty of storage capacity in the surrounding soil of the experimental area. In this way, when water has infiltrated further down than the steel frame that limits the measurement area of the rainfall simulator, water is transported into the surrounding soil by suctional forces. Therefore, water that has infiltrated into the soil is transported away from soil beneath the measurement area of the rainfall simulator. This combined with the fact that the area on which rainfall is irrigated with the rainfall simulator is much smaller than the catchment, the storage capacity of the soil in general is not likely to be exceeded in such an experiment because water can be stored in the surrounding dry soil. Therefore, as the storage capacity of the soil cannot become limiting to infiltration in this experiment, the only limiting factor will be the infiltration capacity of the soil surface. Therefore, it is only possible to measure the infiltration capacity of the surface with the designed physical rainfall simulator presented in **Paper II**. However, it can be very beneficial to be able to isolate infiltration excess runoff, as this most probably is

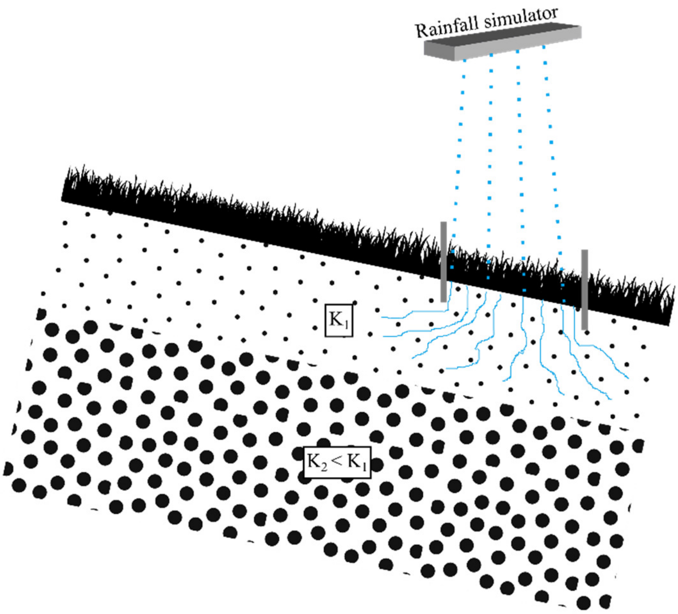

Figure 3.3. *Rainfall simulation during summer where the soil water content is significantly lower than the saturated soil water content.* K_1 *and* K_2 *are the hydraulic conductivities of the upper and lower soil layer respectively.*

the deciding factor on the risk of runoff production during summer under low water content conditions as this is the season where high intensity cloudbursts most frequently occur in Denmark. Finally, by combining the methods of both the large- and small-scale experiments, it is possible to study the three primary runoff types which are subsurface throughflow, saturation excess runoff, and infiltration excess runoff.

The applicability of traditional models to simulate pervious surface runoff were investigated and compared to alternative models in **Paper III**. The performance of the time-area and kinematic wave models were compared to a linear reservoir model, regression-based models, and neural network models. The models were optimised based on measured data from **Paper I**. Generally, it was found that the neural network models generated the best performing models. However, it was also found, that the significantly simpler kinematic wave and linear reservoir models produced reliable and stable results. The time-area model performed slightly worse while the regression models produced the worst model fits.

The reason that the kinematic wave and linear reservoir models seem to perform well is because of their foundation in the continuity equation which contains a storage term (*dy/dt*). This term seems to simulate the storage of water in the upper soil layer and seems to be a significant factor for precise modelling of the measured data from the full-scale field-station presented in **Paper I**. The importance of a storage term in the models was also seen in the neural network models. One neural network was optimised by including only data at current time to estimate the current runoff values. In the second neural network ‘historical’ data of up to 180 minutes behind current time was implemented in the optimisation of the network. These historical data contain previous values of soil water content. It was seen that the implementation of these data increased the performance of the neural network model compared to the utilising only current data values. The reason of this can be found in the historical data, as the neural network in this way have an estimate of the previous time steps water storage in the system.

The use of the kinematic wave and linear reservoir models compared to the neural network models have different pros and cons. The most significant benefit of neural network models is their flexibility in terms of simulating the many variables that is present in a catchment and include these in a single model. These could be physical variables such as morphological and physical characteristics of the catchment in Lystrup. Furthermore, neural networks can also include variables that have not yet been discovered or considered as important to runoff production. The disadvantage of neural networks is that such variables are very likely to stay hidden in the neural network which can be unfortunate in terms of extrapolating results to larger scales and other catchments. Additionally, there is a risk of overoptimization using neural network models. This was investigated in **Paper III** which found that including a large number of neurons in the neural network compared to the number of input variables resulted in a larger divergence of optimisations compared to the use of fewer neurons. Furthermore, as neural networks rely heavily on data, they are typically trained for a specific and unique dataset. This means that neural networks most probably are not transferable to other locations than the measurement area in Lystrup.

The advantage of physically based models such as the kinematic wave and linear reservoir model is their transferability to the physical reality at the experimental site in Lystrup. In this way, these models can be useful in terms of identifying the important factors affecting runoff production from such a location. Furthermore, the kinematic wave and linear reservoir models only have one calibration parameter which make them significantly easier to use. Generally, the kinematic wave and linear reservoir models are designed to simulate only one runoff process. In this way, they are not able to simulate e.g. saturation excess runoff as a secondary runoff process in a single model like the neural network models.

3.2. COMMERCIAL OUTCOMES

This PhD-study has resulted in some surprising observations which were not initially expected. These results can potentially have a large impact on urban drainage design and how urban pervious area runoff should be considered in the future when drainage systems are designed.

The presence of subsurface throughflow and saturation excess overland flow in Lystrup shows that infiltration excess runoff is not the only type of runoff which exists in urban areas. Therefore, future urban drainage models should include the possibility to include subsurface throughflow and saturation excess runoff on equal footing with infiltration excess runoff. Subsurface throughflow is an important aspect to include in future urban drainage design because it has the potential to increase runoff in longer periods during fall and winter and thereby occupy important capacity in the drainage systems. Modelling of subsurface throughflow could be carried out with the kinematic wave model which is often available in commercial models. However, a linear reservoir model and neural network model could be used with even higher accuracy although these models are not standard models in commercial modelling software.

Measurement campaigns as carried out in this project should gain a wider application in the future as such data are powerful for urban drainage engineers to understand the urban hydrological systems. Measurement campaigns are useful for model calibration and could potentially replace some models. For example, rainfall simulator campaigns could replace infiltration excess models because the rainfall simulator gives a relatively accurate estimate of the infiltration capacity as a function of the soil volumetric water content.

Currently, rainfall is practically the only hydrological parameter that is measured for use in urban drainage modelling. However, this study show that future work should be put into measuring the variation of soil hydrological properties such as the soil water content. This could aid in the understanding of the correlation between extraneous water and the soil water content.

Measured relationships between physical properties such as soil characteristics, surface slope, and soil-water properties could be implemented in GIS software for mapping of critical areas which have a high potential of producing runoff. In this way, areas which should have special attention in terms of the risk of runoff production could easily be pointed out.

CHAPTER 4. CONCLUSIONS

Five sub-question were raised to investigate what identifies rainfall-runoff from urban pervious areas and to assess how this corresponds to the current understanding of this topic. The sub-questions are answered below.

Sub-question I: How is rainfall-runoff from urban pervious areas physically quantified?

> Rainfall-runoff from an urban pervious area in Lystrup, Denmark, can be physically quantified using both small- and large-scale experimental approaches. It was found that measured runoff on full-scale in **Paper I** had different characteristics compared to small scale rainfall simulator experiments carried out in **Paper II**. The runoff collection system designed for the rainfall simulator in **Paper II** could potentially be installed for long-term field measurements of rainfall-runoff like the full-scale field station in **Paper I**.

Sub-question II: How frequently does urban pervious surface runoff occur?

> The full-scale field station developed in **Paper I** show that a return period for rainfall-runoff of one year can be expected for the measurement area in Lystrup.

Sub-question III: How do physical rainfall simulators perform in estimating the risk of rainfall-runoff from urban pervious areas?

> The developed rainfall simulator in **Paper II** is a time efficient method to collect qualitative data on rainfall-runoff relatively quickly. However, in this project, it was found that the rainfall simulator is primarily good for investigating infiltration excess runoff due to its small spatial scale. Therefore, it cannot be expected that rainfall simulation identifies all important runoff processes in a catchment.

Sub-question IV: Which is the dominant rainfall-runoff processes from urban pervious areas?

> The established full-scale field station in **Paper I** shows that subsurface throughflow is the most dominant runoff process at the measurement area in Lystrup, occurring at least on a yearly basis. This also seems to be the case for saturation excess runoff, though active in significantly shorter timeframes. Infiltration excess runoff

were not present on full-scale but was observed with the developed physical rainfall simulations in **Paper II**. Physical rainfall simulations showed that infiltration excess runoff can only be produced under extreme rainfall intensities which were not recorded under natural conditions on full-scale within the time frame of this study.

Sub-question V: What are the most important soil parameters in terms of indicating rainfall-runoff from an urban pervious area?

It was found that the soil water content was the most correlated parameter to runoff. The full-scale field station developed in **Paper I** found that subsurface throughflow and saturation excess runoff only occurred if the soil volumetric water content was above 0.34 m^3 H_2O / m^3 soil. This is the point of saturation at the experimental location where soil can no longer retain water by suctional forces. The physical rainfall simulator study also found that the soil water content is a critical parameter in terms estimating the magnitude of infiltration and in this way the potential production of infiltration excess runoff.

Sub-question VI: How do currently applied surface runoff models agree with measured surface runoff from an urban pervious area?

Currently applied surface runoff models in urban drainage are not designed to simulate e.g. subsurface throughflow or saturation excess runoff which were the dominant processes measured on full-scale. On the contrary, these are designed to simulate the runoff characteristics of infiltration excess runoff. Therefore, currently applied models do not agree with the measured surface runoff in this study. In **Paper III**, it was found that the traditionally applied time-area and kinematic wave models could be calibrated and optimised to simulate subsurface throughflow with a reasonable performance. However, even better alternatives can potentially be found with linear reservoir and neural network models depending on the acceptable model complexity and data available for model calibration and optimisation.

In conclusion, this study indicates that an urban pervious area that have a high risk of producing rainfall-runoff is identified by having a high soil water content during fall and winter whereas runoff is produced on a yearly basis. This is a typical scenario where subsurface throughflow and saturation excess runoff are the dominating runoff processes. The designed rainfall simulator revealed that the production of infiltration excess runoff requires extreme rainfall intensities which occur less frequently. The measured runoff processes of the pervious area in this study are best represented by models which include water storage like the kinematic wave and linear reservoir model, or alternatively neural network models.

CHAPTER 5. FUTURE PERSPECTIVES

This PhD-study has shown that measurements of rainfall-runoff from urban pervious areas are valuable in terms of quantification and identification of the present runoff processes. The field experiments revealed processes such as subsurface throughflow which were not initially thought of as a possible runoff type in an urban area in relation to current Danish modelling practice. However, the measurements carried out in this study practically only covers an infinitely small part of the potential parametric variation which can be expected on a national or global scale. Generally, this means that the runoff regimes must be expected to vary significantly both in quantity and runoff types in other geographical areas.

Another important aspect that could have a large impact on urban pervious surface runoff is the projected climate changes. Climate changes will in some areas result in higher rainfall intensities during summer and increased accumulated rainfall volumes during winter (Intergovernmental Panel on Climate Change, 2015). These are two meteorological scenarios that will both increase the potential for runoff production. Increased rainfall intensities during summer means that the infiltration capacity of soils will be exceeded more frequently, while increased accumulated rainfall volumes will cause the storage capacity of soils to be exceeded more frequently.

The potential large variation in variables that can affect runoff and future climate changes introduce a substantial uncertainty of what can be expected in the future of urban pervious surface runoff. Therefore, there is a need for more experimental trials to investigate urban pervious surface runoff under varied parametric conditions to increase the quality of urban drainage design in the future.

To investigate the influence of pervious surface runoff in urban drainage systems further a new research and development project has already started by the end of 2018 named *'Monitoring of rainfall-runoff from urban pervious areas two'* (in Danish: *'Monitering af Overfladeafstrømning fra Grønne Områder To'* (MOTO)). The project applies the methods developed in this industrial PhD-study but have the general goal of quantifying the influence of pervious surface runoff on a larger scale by comparing measured runoff in smaller catchments, such as the experimental full-scale field station in Lystrup, to the inflow at the receiving wastewater treatment plants.

Afterwards, it is the plan to scale the ideas and concepts gained from this PhD-study and the research and development projects MOGO and MOTO to a national Danish monitoring program for urban pervious surface runoff. This should result in a large research and development project which maps and indicates the risk of runoff from a wide variety of different surface and soil types.

This project has shown that soil-water properties are very important to the risk of runoff production from pervious surfaces. However, basic soil science is rarely included in the decision making in urban drainage models. Mapping of basic soil-water properties and soil characteristics should be included in future urban drainage design as relatively simple parameters can bring valuable information on the risk of runoff.

Finally, the results of this project clearly indicate that the return period of rainfalls do not stand alone in terms of deciding the risk of runoff from pervious areas. On the contrary, the risk of runoff is especially decided based on a combination of critical soil water content levels and the rainfall type. Therefore, future research projects should investigate how urban drainage systems could be designed based on the state of the entire hydrologic system and in that way use return periods for the entire hydrologic system for future decision making in urban drainage design.

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