

# **ADJUSTMENT OF RAINFALL ESTIMATES FROM WEATHER RADARS USING IN-SITU STORMWATER DRAINAGE SENSORS**

by

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Dissertation submitted December 2015



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Thesis submitted: December 22<sup>nd</sup>, 2015

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Published 2015 by:  
Aalborg University  
Department of Civil Engineering  
Sofiendalsvej 9-11  
DK-9200 Aalborg SV, Denmark

Printed in Aalborg at Aalborg University

ISSN: 1901-7294  
DCS Thesis No. 73

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# THESIS DETAILS



**Ph.D. title:** Adjustment of rainfall estimates from weathers radars using in-situ stormwater drainage sensors

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**Supervisor:** Associate Prof. Michael Robdrup Rasmussen

## List of papers:

- Paper I: Ahm M., Thorndahl S., Rasmussen M. R. & Bassø L., (2013), Estimating Subcatchment Runoff Coefficients using Weather Radar and a Downstream Runoff Sensor, *Water Science and Technology*, 68(6), 2013, p. 1293-1299, DOI: <http://dx.doi.org/10.2166/wst.2013.371>
- Paper II: Ahm M. &, Rasmussen M. R., (2015), Rainfall measurement based on in-situ storm drainage flow sensors, *Urban Water Journal*, DOI: <http://dx.doi.org/10.1080/1573062X.2015.1057176>
- Paper III: Ahm M. &, Rasmussen M. R., (2015), Weather radar adjustment using runoff from urban surfaces, *Journal of Hydrologic Engineering*, DOI: [http://dx.doi.org/10.1061/\(ASCE\)HE.1943-5584.0001299](http://dx.doi.org/10.1061/(ASCE)HE.1943-5584.0001299)
- Paper IV: Ahm, M., Thorndahl, S., Nielsen J.E. and Rasmussen, M. R. (2016), Estimating CSO discharge: A software sensor approach. Manuscript submitted to *Urban Water Journal*.
- Paper V: Ahm, M., Thorndahl, S. and Rasmussen, M. R. (2016) Urban rainfall-runoff measurements: A case study of separating rainfall flows in a complex combined sewer catchment. Manuscript prepared for *Water Science and Technology*.
- Paper VI: Ahm, M., Thorndahl, S., Nielsen J.E. and Rasmussen, M. R. (2016), Weather radar bias adjustment using in-situ storm drainage sensors. Manuscript prepared for *Journal of Hydrology*.

*This thesis has been submitted for assessment in partial fulfilment of the PhD degree. The thesis is based on the scientific papers listed above. Parts of the papers are used directly or indirectly in this thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.*



# PREFACE

The present thesis “Adjustment of rainfall estimates from weathers using in-situ stormwater drainage sensors” has been prepared as the finalization of a Ph.D. study carried out at the Department of Civil Engineering, Aalborg University. The Ph.D. study is a part of the Danish Council for Strategic Research project: Storm- and Wastewater Informatics (SWI). The SWI project partners include two universities (Aalborg University (AAU) and the Technical University of Denmark (DTU)), a research institute (Danish Meteorological Institut (DMI)), two private companies (DHI A/S and Krüger A/S) and three of the largest utility companies in Denmark (BIOFOS A/S, HOFOR A/S and Aarhus Water A/S).

The overall objective of the SWI project is to close knowledge gaps within rainfall prediction from weather radars and control of integrated urban waste and stormwater systems. On the basis of this knowledge it is possible to reduce the health risk for citizens and environmental impact from combined sewer overflows, reduce the extent of structural damage related to flooding from urban drainage systems, and reduce the cost of operation, maintenance, and expansion of sewer systems and treatment plants. The central output of the project is key knowledge for future development of intelligent real-time decision support systems by describing the precipitation processes from the drop formation in the clouds, throughout the sewer and treatment system, and finally into the receiving waters (SWI, 2008).

This Ph.D. project contributes to the knowledge of weather radar adjustment for urban drainage applications. The overall objective of this project is to improve the precipitation estimates from weather radars to improve the predictions of flow and water levels in urban drainage systems.

I would like to thank my supervisor Associate Professor Michael Robdrup Rasmussen for giving me the opportunity to realize this Ph.D. project, and for his enthusiastic guidance and support throughout the study. I would like to thank my colleagues Assistant Professor Jesper Ellerbæk Nielsen and Associate Professor Søren Liedtke Thorndahl for support and professional discussion during the study, and colleague Mai Brink Rasmussen for her help creating the graphical illustrations in this thesis.

I would like to thank the partners and colleagues in the SWI project, especially Aarhus Water for providing stormwater runoff data and DMI for providing weather radar data for my case studies. Furthermore, I would like to acknowledge COWI A/S, Søren Enggaard A/S and C.W. Obel Ejendomme Aalborg for their involvement in the realization of the measurement station *BEWARE* established in central Aalborg.

Finally, I would like to thank my family and friends for their everlasting support, love and encouragement during my studies. It has truly meant the world for me.

Aalborg, December 2015

Malte Kristian Skovby Ahm





# ENGLISH SUMMARY

The topic of this Ph.D. thesis is adjustment of weather radar rainfall measurements for urban drainage applications by the use of in-situ stormwater runoff measurements. It is possible to obtain the high spatiotemporal resolution rainfall data desired for advanced distributed urban drainage applications by the use of weather radars. Rainfall data representing the spatiotemporal distribution is a necessity for accurate modelling and real-time control of distributed urban drainage systems.

Weather radar measurements are indirect measurements of the rainfall in the atmosphere, which poses some challenges for using the data in urban drainage applications. There are discrepancies between radar-rainfall measured in the atmosphere and the “true” rainfall at ground level. Consequently, radar-rainfall estimates are usually adjusted to rainfall observations at ground level from rain gauges. When radar-rain gauge adjusted data is applied for urban drainage models, discrepancies between radar-estimated runoff and observed runoff still occur. The aim of urban drainage applications is to estimate flow and water levels in critical points in the system. The “true” rainfall at ground level is, therefore, of less importance as long as the estimated flow and water levels are correct. It makes sense to investigate the possibility of adjusting weather radar data to rainfall-runoff measurements instead of rain gauge measurements in order to obtain better predictions of flow and water levels.

This Ph.D. study investigates how rainfall-runoff measurements can be utilised to adjust weather radars. Two traditional adjustments methods based on rain gauges were used as the basis for developing two radar-runoff adjustment methods. The first method is based on the Z-R relationship describing the relation between radar reflectivity (Z) and radar rainfall rate (R). A Z-Q relationship were developed to describe the relation between radar reflectivity (Z) and radar rainfall runoff (Q). The second method is based on the radar-rain gauge mean field bias adjustment approach. A radar-runoff bias adjustment approach was developed. The second method is less computationally heavy and easier to implement in larger complex urban catchments since the method does not require a runoff model to describe the transfer function between rainfall and runoff.

The two radar-runoff adjustment methods were tested under real practical conditions using two different case study sites. Both methods performed similar to the radar-rain gauge adjustment methods when comparing radar predicted rainfall-runoff against observed rainfall-runoff. However, the performance of the radar-rain gauge adjustment methods decreases when only based on rain gauges located outside the given catchment. This Ph.D. study has proved that it is possible to adjust weather radar measurement using measured rainfall-runoff.

The main challenge of using radar-runoff adjustment methods is to close the rainfall-runoff mass-balance. In complex combined sewer catchment with CSOs, basins, pumps, etc. it can be very difficult to close the rainfall-runoff mass-balance. A great effort of the Ph.D. project was dedicated to developing methods for closing the rainfall-runoff mass-balance. A closed mass-balance is also important for accurate calibration of the urban drainage models used of the analyses and real-time control. Hence, some of the work performed during this Ph.D. can also be used for improving calibration of urban drainage models.



# DANSK RESUME

Emnet for denne Ph.D.-afhandling er justering af vejrradar regnestimater til afløbsteknik anvendelse ved brug af afstrømningsmålere i afløbssystemet. Ved brug af vejrradare er det muligt at måle regnen med den stedlige og tidlige opløsning, som ønskes for avanceret afløbsteknik modellering af distribuerede afløbssystemer. Det er nødvendigt at anvende data, som repræsenterer den stedlige og tidlige variabilitet af regnen, for at kunne modellere regnafstrømning korrekt i distribuerede afløbssystemer samt anvende reeltidsstyring til at styre disse distribuerede systemer.

Vejrradare måler regnen indirekte i atmosfæren, hvilket giver nogle udfordringer i forhold til at anvende vejrradardataene i afløbstekniske sammenhænge. Der kan oftest observeres afvigelser mellem det radarmålte regn i atmosfæren og hvad der måles ved jordoverflade. Vejrradardata er derfor ofte justeret til regnmålere for bedre at repræsentere regnen ved overflade. Når de justerede vejrradardata anvendes til afløbsteknik modellering, observeres der oftest afvigelser mellem den estimerede regnafstrømning og den målte regnafstrømning. I afløbstekniske sammenhænge er det mere vigtigt at kunne estimere regnafstrømning, og derved flow og vandstande i kritiske punkter af afløbssystemet, end det er at kunne estimere regnen korrekt ved overflade. Det giver derfor mening at undersøge muligheden for at justere vejrradardata til afstrømningsmålinger for at forbedre forudsigelsen af flow og vandstanden.

Dette Ph.D.-studie har undersøgt, hvordan målinger af regnafstrømning kan anvendes til at justere vejrradare. To justeringsmetoder baseret på afstrømningsmålinger er blevet udviklet. Metoderne er baseret på to traditionelle radar-regnmåler justeringsmetoder. Den første metode er baseret på Z-R forholdet, som beskriver forholdet mellem radar refleksivitet (Z) og radar regnintensitet (R). Et Z-Q forhold blev udviklet, som beskriver forholdet mellem radar refleksivitet (Z) og radar regnafstrømning (Q). Den anden metode er baseret på en radar-regnmåler bias justering (mean field bias adjustment). En radar-regnafstrømning bias justering blev udviklet. Den anden metode er mindre beregningstung og nemmere at implementere for et større komplekst opland. Det er ikke nødvendigt at bruge en afstrømningsmodel til at beskrive forholdet mellem regn og regnafstrømning ved anvendelse af den anden metode.

De to justeringsmetoder baseret på afstrømningsmålinger blev testet under praktiske forhold ved brug af to forskellige oplande. Begge metoder præsterede på samme niveau som radar-regnmåler justeringsmetoderne. Sammenligningen var baseret på radar estimeret og målt regnafstrømning. Niveauet faldt dog for regnmåler justeringsmetoderne, hvis de kun blev baseret på regnmålere uden for oplandet. Dette Ph.D.-studie har vidst, at det er muligt at justere vejrradare ved brug af regnafstrømningsmålinger.

Den største udfordring ved at bruge justeringsmetoder baseret på regnafstrømning er at lukke massebalancen for regnafstrømningen. Hvis oplandet indeholder overløbsbygværker, bassiner, pumper ol. kan dette være meget besværligt. En stor del af Ph.D.-studiet er brugt på at udvikle metoder til at lukke massebalancen. En lukket massebalancen er også vigtig for præcis kalibrering af afløbstekniske modeller anvendt til analyse og reeltidsstyring. En del af arbejdet i dette studie kan derfor også anvendes til at forbedre kalibreringen af afløbstekniske modeller.



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# CHAPTER 1. INTRODUCTION

The human life expectancy in developed countries have approximately doubled to 75 years during the period 1840-2000 (Oeppen, 2002). The increased life expectancy is the result of advances in income, salubrity, nutrition, education, sanitation, and medicine (WHO, 1999). Access to clean drinking water and sanitation is one of the most important factors for public health (Mara et al., 2010). In 2007 readers of the British Medical Journal voted the “sanitary revolution” as the greatest medical advance since 1840 (Ferriman, 2007). However, today almost one tenth of the global burden of disease are still associated with poor water supply, sanitation, hygiene and water resource management (Prüss-Üstün et al., 2008). Ongoing investment in good sanitary conditions in developing counties as well as in developed counties is an important task to maintain and improve public health.

The main purpose of urban drainage systems are to effectively divert waste- and stormwater away from urban areas to protect the inhabitants and environment. However, to what extent and how this goal is reached is a political socioeconomic prioritisation. The development of modern urban drainage systems in Europe have been characterised by the health aspect, which often have resulted in the following political prioritisation:

1. Protect the population from the health risk associated to exposure to wastewater and against flooding.
2. Protect private and public values against flood damage.
3. Protect the environment from pollution and hydraulic overload.

Heavy rainfall can result in stormwater loads, which exceed the design load of a given urban drainage systems. A hydraulic system overload can result in pollution, health risks, flooding, inconvenience for society and damage material property etc. Therefore, accurate measurement and prediction of rainfall is essential for both design, analyses and real-time control (RTC) of urban drainage systems. However, the requirements to the rainfall data is different for these applications.

**Design** covers the planning of drainage systems for new urban areas, urban regeneration and urban expansion. The design process is usually based on a statistical correlation between rainfall intensity and duration, called Intensity Duration Frequency (IDF). The statistical correlation is normally based on decades of rainfall data from multiple rain gauges.

**Analysis** (modelling) is used to clarify the cause of a hydraulic overload after a severe storm event, and how it can be avoided in the future. Analyses are based on historical time series of rainfall data, which traditionally are obtained from rain gauges.

**Real-time control** is modelling and control of urban drainage systems in real-time during the storm event to actively utilise the full capacity of the drainage system by adjusting basin levels, gates, pumps, overflows etc. RTC is based on current states of the drainage system, rainfall measurements from the near past and rainfall predictions of the near future.

Traditionally, urban hydrologist have relied on precipitation measurement from rain gauges for both design, analysis and RTC. However, rain gauges are point measurements and only representative for a limited range. Hence, a dense rain gauge network is needed for proper representation of the spatiotemporal rainfall variability, especially during highly convective storm events. For analysis and RTC of larger distributed urban drainage systems, a good representation of the spatiotemporal rainfall distribution near the ground is crucial to predict flow and water levels correctly. Advances in civil weather radar technology during the latest decades have made high spatiotemporal resolution rainfall data accessible to urban hydrologist. Furthermore, rainfall predictions of the near future can be obtained using numerical forecast models based on weather radar data from the near past.

Weather radar measurements are indirect measurements of the precipitation in the atmosphere, which poses some challenges for using them in urban drainage applications. High-resolution weather radar data usually contains a good representation of the relative spatiotemporal rainfall distributions, but it is a challenge to quantify the exact rainfall intensities near the ground solely relying on weather radars. Consequently, weather radar measurement are often adjusted to ground observations to ensure accurate quantitative precipitation estimates (QPE). Traditionally, rain gauges are used for radar adjustment.

Rain gauges have historically proven their worth in relation to urban drainage. They are often assumed accurate and interpreted as the “true” rainfall at ground level. However, they can be subject to substantial uncertainties, and are only representative for rainfall within a limited range. The available rain gauge density for weather radar adjustment is often low. Hence, radar rainfall estimates adjusted to rain gauges may inherit significant representativeness errors. When applying rain gauge adjusted radar QPE to urban drainage models larger deviations are often observed between modelled and observed runoff.

The aim of urban drainage weather radar applications are often to predict flow and water levels accurately in critical points in the drainage systems. Hence, accurate prediction of the true rainfall at surface level is less important as long as the predicted flow and water levels are correct. Consequently, it may be beneficial to adjust radar rainfall estimates to runoff measurements in the given catchment. Rainfall-runoff measurements are indirect measurements of the part of rainfall that runoff to the urban drainage system. Hence, the part of the rainfall that is important to predict accurately.

If it is possible to use runoff measurements for weather radar adjustment. Then the amount of available adjustment sensors would significantly increase since in-situ runoff sensors typically are available in urban drainage catchments. It is important to underline that the radar-rain gauge and radar-runoff adjustment approaches are not viewed as mutually exclusive, but as complimentary to improve prediction of urban rada-rainfall-runoff.

## **1.1. MOTIVATION AND RESEARCH OBJECTIVES**

It is not a trivial task to obtain accurate high spatiotemporal resolution rainfall measurements for urban drainage applications. Furthermore, all rainfall measurements are interpretations of the true rainfall. No matter if, the rainfall is measured with a radar, rain gauge or indirectly via rainfall-runoff measurements. All measurements are associated with uncertainties.



Accurate high spatiotemporal resolution rainfall estimates are essential for urban drainage applications in relation to accurate predictions of flow and water levels. Today, high spatiotemporal resolution rainfall estimates are available in the form of weather radar QPE. To obtain accurate rainfall estimates from weather radars, it is necessary to adjust the weather radar QPE to ground observations.

The aim of urban drainage applications (analyses and RTC) are to predict flow and water levels accurately. The accuracy of the rainfall prediction is often less important as long as flow and water levels are predicted accurately. Consequently, it make sense to investigate the possibility of adjusting weather radar QPE to runoff measurements instead of the traditional adjustment basis, rain gauges. As a result, process and model uncertainties are included into the adjusted radar rainfall estimate (aggregated uncertainty).

The main objective of this Ph.D. thesis is to investigate the potential of using runoff measurements from in-situ stormwater drainage sensors to adjust and improve weather radar QPE for urban drainage applications.

Based on the main objective, the following research objectives have been formulated:

1. How can runoff measurements be utilised to measure rainfall intensities, and how does these sensors compare to tradition rain gauges?
2. It is better to use runoff measurements from the given catchment than one or more rain gauges placed within or outside the catchment to adjust weather radar QPE for urban drainage applications?
3. How can the stormwater mass balance be ensured for modern complex urban drainage systems, which included basins, pumps, CSO's, infiltration, exfiltration, etc.?

These research objectives have formed the basis for the research conducted through this Ph.D. study. Section 1.2 describes the strategy and delimitations of the research and section 1.3 describes the thesis structure. The six supporting papers for this thesis (summarised in chapter 5) describes the studies performed to answer the research objectives.

## **1.2. RESEARCH APPROACH**

Different research approaches can be used to investigate the research objectives of this thesis. The goal of the research project: Storm- and Wastewater Informatics (SWI), which this Ph.D. study was a part of, was to close knowledge gaps within rainfall prediction from weather radars and control of integrated urban waste and stormwater systems. Hence, the goal was to mature the technology in a pragmatic manner, so weather radar QPE can be used to predict flows and waters levels accurately in stormwater drainage systems.

This thesis investigates the possibility of a shortcut to reliable prediction of flow and water levels in drainage systems by adjusting weather radar QPE to runoff measurements. Consequently, the research approach of this Ph.D. study was domination by the pragmatic research approach (Menand, 1997). Hence, it was acknowledged that all knowledge are approximate and incomplete, and its value depend on how well it solves the problem.

The ambiguities observed between rainfall and runoffs measurements are caused by; an incomplete understanding of the actual physical transfer processes between rainfall and runoff, limited and uncertain measurement data, and limited complexity of transfer models.

The practical “truth” in the perspective of this approach is the observed runoff in the stormwater drainage system. Hence, the radar QPE is an “input parameter”, which can be adjusted to aggregate all the uncertainties related to the transfer functions between rainfall and runoff observations.

Two different case study locations were used to investigate the research objectives described in section 1.1:

- A small urban catchment, where all uncertainties related to the runoff process can be investigated and quantified if necessary.
- A large urban catchment with all its complexities and uncertainties.

By the use of the small urban catchment, it was possible to test and quantify the quality of the methodologies developed in this Ph.D. study under favourable and controlled conditions. The main uncertainties were related to measurement uncertainties of rainfall and runoff. By the use of the larger urban catchment, the methodologies were tested under real practical conditions.

### **1.3. THESIS STRUCURE**

This thesis contains seven chapters and six associated appendices related to the objective described in the two previous sections.

**Chapter 1** introduced the background and motivation for this study.

**Chapter 2** present the societal context of this study.

**Chapter 3** present the scientific context of this study.

**Chapter 4** present the case study areas used for the work carried out in this study.

**Chapter 5** present the runoff based weather radar adjustment concept along with summaries of the papers, which is the basis for this thesis. The summaries haven been focused towards the subjects of this thesis.

**Chapter 6** provides the conclusion of the work carried out in this study along with perspectives of the work and suggestions for future work.

**Appendix A-F** contains a full version of the supporting papers for this thesis.

# CHAPTER 2. URBAN DRAINAGE IN A SOCIETAL CONTEXT

An introduction to urban drainage is given through this chapter to clarify the societal context of this thesis. Urban drainage systems are constantly evolving according to the present political socioeconomic prioritisation. The life span of urban drainage systems are usually more than hundred years. Consequently, the current layouts is a combination of different political socioeconomic prioritisations and different design practises based on knowledge of hydraulics, sanitation and environmental impact that have improve through the ages. Some of the present urban drainage challenges in Denmark are related to historical design choice.

## 2.1. URBAN DRAINAGE THROUGH THE AGES

The concept of urban drainage and sanitation are often considered an “invention” of the modern civilisation motivated by the cholera epidemics in the larger European cities in 19<sup>th</sup> century. However, the concept was merely “reborn” in the start of the 19<sup>th</sup> century after the “Sanitary Dark Ages”. Many of the basic principles in modern sanitation can be traced back to ancient civilisations. Lofrano and Brown (2010) suggest, that the evolution of urban drainage and sanitation practices can be divided into five main periods:

- Early history (ca. 8000 B.C. – ca. 800 B.C.)
- Roman period (ca. 800 B.C. – ca. 400 A.D.)
- Sanitation dark ages (ca. 300 A.D. – ca. 1800 A.D.)
- Age of sanitary enlightenment (ca. 1800 A.D. – ca. 1970 A.D.)
- Age of stringent environmental standards (ca. 1970 A.D. – present)

The first three periods are of minor relevance for this thesis, but an overview of the history from these periods can be found in several articles (e.g. Burian and Edwards, 2002; Angelakis et al., 2005; Vuorinen et al., 2007; Lofrano and Brown, 2010; de Feo et al., 2014). The recent history is relevant for the societal context of this thesis, since the life span of urban drainage systems often are 100 years or more. Hence, older parts of the current urban drainage systems in Denmark were developed and constructed during the “Age of sanitary enlightenment” (Lofrano and Brown, 2010) and does not meet the requirements of the present design practice.

The “Age of sanitary enlightenment” started with the industrialization and associated urbanisation throughout the 18<sup>th</sup> century. During the first cholera epidemic in London in 1831-1832 it was noticed, that the outbreak was more intense in dirty and humid areas of London, while elevated and dry areas were less affected. The “Public Health Art” was enacted in 1848 and in 1865; a sewer system throughout London was completed. Other larger European cities constructed sewers in the same period and the following decades. All of these systems were designed after the assumption “the solution of pollution is dilution” (Butler and Davie, 2010; Lofrano and Brown, 2010; Winther et al., 2011; de Feo et al., 2014). Hence, environmental and sanitary problems were just relocated to outside the cities.

The cholera epidemics lead to the realisation that it is potentially fatal for humans to live close together in sedentary societies due to serious health risks from waterborne diseases. Hence, it is necessary to address the sanitary challenges to sustain modern cities. A recent example of the consequence of insufficient sanitary conditions is the aftermath of the 2010 Haiti earthquake. Nine months after the earthquake the worst cholera epidemic in recent history broke out. By July 2015 the number of confirmed cases reached 745,000 with a death toll of 8,825 (OCHA, 2015).

In Denmark, construction of combined sewer systems (waste and stormwater is mixed) started in Copenhagen in 1860. Initially the sewer system in Copenhagen was planned as a separated system (waste and stormwater in different pipes), but due to political and economic conditions, a combined system was chosen. This choice became the standard for the Danish sewer systems until the 1960s, when some cities began to construct separated sewer systems (Winther et al., 2011). Today most new urban areas are developed with separated sewers, and when conditions permit, older combined sewers are replaced with separated sewers. Figure 1 illustrates how combined and separated sewers work during dry and wet weather.

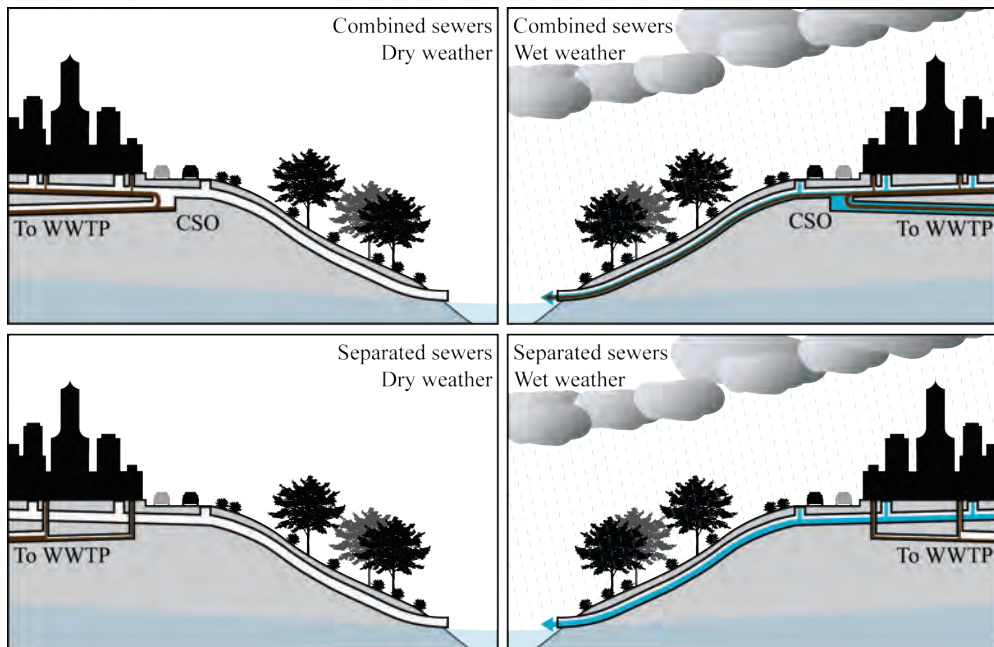


Figure 1: Illustration of how combined and separated sewers work during dry and wet weather. When using a separated system, only rainfall-runoff is discharged to the recipient during wet weather. If the system capacity is exceeded during wet weather for a combined system, the exceeding combined sewage (sewage and rainwater) is discharged to the recipient via a combined sewer overflow (CSO).

During the first part of the 20<sup>th</sup> century it was realised, that the assumption “the solution of pollution is dilution” was not viable. Wastewater treatment plants (WWTP) were constructed to remove pollutants. Requirements to treatment of wastewater from all Danish cities were implemented during the 1960s. The treatment technology were mainly based on mechanical and biological treatment, with some exceptions of chemical treatment.

WWTPs have an upper hydraulic load limit due to the different treatment processes. When this load limit is reached (normally during wet weather for combined sewers), the excess combined sewage is discharged directly to the recipient (receiving waterbody) via a combined sewer overflow (CSO) without any treatment (Figure 1). CSOs are “failsafe’s”, which ensure a controlled release of excess water during wet weather when the system load is larger than the design load.

Until the 1970s the hydraulic design loads for Danish WWTPs (and CSOs) were based on a mixing ratio principle between waste and stormwater (WPC, 1953). The mixed excess water during wet weather were presumed less problematic for the recipient if the wastewater were diluted enough before discharge. The typically used mixing ratio were 1:5 or 1:6 (1-part wastewater and 6-part stormwater). Hence, the hydraulic design load were 6-7 times the dry weather flow.

The typically used mixing ratios were based on the assumption that concentrated wastewater had an oxygen demand of approx. 60 mg/l and that the oxygen concentration in stormwater was 10-12 mg/l. Hence, at mixing ratio of 1:5 to 1:6 would balance the oxygen demand of the wastewater and prevent oxygen depletion in the recipient. However, today it is known, that concentrated wastewater have a biochemical oxygen demand (BOD<sub>5</sub>) and chemical oxygen demand (COD) of approx. 350 mg/l and 750 mg/l, respectively (Hvitved-Jacobsen et al., 2010). In additions, CSO events will also include pollutants originated from erosion and resuspension of temporarily accumulated sewer solids (sewer sediments and biofilms). Hence, the conceptual model understanding of the viable dilution principle was not correct.

Beside the pollutant load, a CSO event will also result in a hydraulic load of the recipient. For streams etc. the hydraulic load of the recipient can be more severe than the pollutant load since a high hydraulic load can result in severe bed erosion. Hence, fauna and flora can be “washed out” of the stream.

The commercially available gas chromatography and atomic absorption spectrophotometry in the 1970s allowed for accurate characterization of pollutants. This resulted in a better understanding of environmental contamination (Lofrano and Brown, 2010). However, the process of understanding the effects of pollutants, and how they interact with the environment in combination is far from finished.

Since the 1970s several Danish and European Union acts have been enacted to protect water resources. A brief overview of the complex administrative and legal aspects regulating discharge of waste and stormwater (urban runoff) is given here. The four main European directives, which have regulated the discharge of urban runoff are listed here:

- 1976 - The Bathing Water Directive ([76/160/EEC](#))
- 1991 - The Urban Waste Water Treatment Directive ([91/271/EEC](#))
- 2000 - The Water Framework Directive ([2000/60/EC](#))
- 2006 - The New Bathing Water Directive ([2006/7/EC](#) repealed [76/160/EEC](#)).

European directives are legal acts, which member states must adopt via national legislative procedures. The main Danish legislation, which have regulated the discharge of urban runoff are listed here:

- 1974 - Environmental Protection Act (Miljøbeskyttelsesloven)
- 1983 - Act on Watercourses (Vandløbsloven)
- 1987 - Water Environment Plans I (Vandmiljøplan I)
- 1998 - Water Environment Plans II (Vandmiljøplan II)
- 2004 - Water Environment Plans III (Vandmiljøplan III)
- 2009 - Act on Environmental Goals (Miljømålsloven)

The Environmental Protection Act and the Act on Watercourses have been revised several times since they were enforced the first time. The three Water Environment Plans and the Act on Environmental Goals are the most comprehensive implementations of the stated European directives in Denmark.

The focus of the Water Environment Plans were to reduce the release of nutrients from wastewater and agriculture to the environment. The Act on Environmental Goals is an implementation of the European Water Framework Directive ([2000/60/EC](#)). The objective of the directive is to ensure a “good water quality” in all watercourses, lakes, coastal waters, and groundwater in Europe by 2015. According to the directive “good water quality” for a given water environment means, that the state of the given water environment should be close to an unaffected reference state.

According to the Water Frame Directive, each member state must formulate management plans to reach the environmental goals. The first plans should be published by December 2009. Hereafter, a revision of the plans are required every sixth year. Denmark, published the second plans December 2015 and these apply until 2021. Quantification of the “good water quality” is based on three index’s; a flora index, a fauna index, and a fish index. Because of the increased environmental awareness, discharge permits for urban runoff will presumably be based on ongoing environmental impact assessments of the receiving water bodies in the future. Today, these permits are based on static requirements in Denmark.

The increased environment awareness have characterised the urban drainage development in Denmark since the 1970s. To reduce the release of pollutants and ensure a “good water quality”, Danish water utility companies are continuously improving wastewater treatment and mitigating CSOs by replacing combined sewers with separated sewers and increasing system capacity. However, replacing existing combined sewer is a comprehensive and very expensive task, which will still take several decades to complete. The main benefit of separating is the reduced environmental impact from CSO. Another benefit is the reduction and predictability of the water volume that needs to be treated at the WWTP. Hence, the treatment processes can be optimized. However, stormwater still contain pollutants (e.g. heavy metals) washed off from urban surfaces. Simple treatment in the form of sedimentation in detention ponds is needed before stormwater is released to receiving waterbodies.

Beside the increased environment awareness, the development have also been characterised by increased awareness of climate changes and urban stormwater flooding during the latest decades. Both combined and separated sewers are designed to handle stormwater. However, the consequences of stormwater flooding from combined sewers is more critical than from separated sewers due to the health risks for humans associated to exposure to wastewater.

Design of urban drainage systems is a balance between the cost of flooding and capital investment, which is expressed as the “service level”. The Water Pollution Committee (WPC) of The Society of Danish Engineers have defined the Danish design practice for urban drainage systems by defining the accepted frequency of urban flooding (WPC, 2005). Local water authorities may apply more strict requirements voluntarily, if they assess, that the “service level” should be higher than defined by WPC.

- Combined systems (mixed waste and stormwater): Once every ten years.
- Separated systems (only stormwater): Once every five years.

The actual stormwater design loads corresponding to the “service levels” are normally based on IDF’s from WPC. The IDF’s are based on data from six rain gauges installed in the 1930s (phased out during the 1960s), and a national rain gauge network started in 1979 by WPC. Today, the WPC network consists of 157 active rain gauges (WPC, 1950, 1953, 1974, 2006, 2008, 2014). In principle, an IDF is only valid for the location of the rain gauges during the data period. Hence, the IDF is a guess of future rainfall characteristics based on past rainfall characteristics.

When designing stormwater drainage systems two different scenarios are typically used; (1) heavy rainfall intensities and (2) large rainfall volumes from low intensity long-duration rainfall. Heavy rainfall will typically cause capacity problems locally in pipes and channels whereas large rainfall volumes will cause capacity problems in basins. A combination of these two rainfall scenarios also occur naturally, but they are rarely analysed in combination in the design situation. Especially the combination where low intensity long-duration rainfall are followed by high intensity rainfall can cause problems. In these cases, basins are often partially full when the heavy rainfall starts. Consequently, a potential flooding will be more severe than anticipated since the basin volumes already are used.

Since 2005, the drainage design recommendations from WPC have included guidelines for incorporating climate changes into the estimation of stormwater design loads (WPC, 2005, 2008, 2014). The design loads are adjusted for climate changes by applying a climate factor corresponding to the expected increase in rainfall intensities for a given return period. However, it were first with the release of the updated recommendations in 2008 and 2014, that detailed analyses had been performed. The analyses were based on the A2 climate scenario from the Intergovernmental Panel on Climate Change (IPCC, 2000). According to the latest recommendations (WPC, 2014), a climate factor of 1.3 should be used for design loads (30% increase). Consequently, new urban drainage systems in Denmark are designed for the expected effects of climate changes. However, the main part of the Danish drainage systems are constructed before 2005. Hence, the main part of the drainage system are not designed for the expected climate changes.

## 2.2. PRESENT CHALLENGES FOR URBAN DRAINAGE IN DENMARK

Urban flooding and combined sewer overflow (CSO) is not necessarily the results of badly designed drainage systems or malfunctions drainage systems, but the result of political socioeconomic prioritisation and decades of continuous construction, expansion and renovation. As described in the previous section, the present layout of the urban drainage systems in Denmark is a result of continuously development over the last century with varying design requirements. Consequently, the present capacity of our urban drainage systems are often asymmetrical.

Newly constructed parts of the drainage systems are designed to handle the expected effects of climate changes and current environmental requirements. Whereas older parts of the drainage systems are not designed for these requirements. Replacing and renovating existing systems to meet the current standards is a comprehensive and very expensive task, which will still take several decades to complete.

Meanwhile, two main strategies exist to minimise the effects of urban flooding and CSO:

**Passive control:** No intervention during the rainfall event. If an urban flooding occur, advanced analyses of how and why the urban flooding occurred are performed subsequently. Based on the analyses, it is decided whether or not, and how, the systems can be improved for future events.

**Active control:** Intervention during the rainfall event. The urban drainage system is controlled actively in real-time by adjusting basin levels, gates, pumps etc. to prevent or minimise the effects of the urban flooding. E.g. by flooding less important areas (e.g. green areas) instead of residential areas. Subsequently, analyses can be made to improve the system.

Traditionally, urban drainage systems is designed for passive operation. When using IDF's for design the rainfall is assumed to be uniform in space and time. However, extreme rainfall, which causes urban flooding in Denmark (temperate coastal climate), is usually highly convective rainfall. Highly convective rainfall is not uniform in space and time. It has a spatiotemporal variability down to a few kilometres and often less than 30 minutes. Hence, only parts of a city may be affected and flooded leaven the rest of the city unharmed and with extra capacity in the drainage system.

Unutilised capacity leaves a potential for optimizing the drainage management if future states can be predicted accurately. With the advances in hydrology modelling, rainfall measurement and short-term rainfall prediction during the latest decades it is today possible to perform advanced analysis and RTC of urban drainage systems to minimise urban flooding (Schütze et al., 2004; Fletcher et al., 2013). It is important to underline, that RTC is not the solution for severe urban flooding in itself. It can only help to utilise the system capacity more efficiently and prioritise where flooding and CSO occur. If the rainfall is more severe than the system can handle when fully utilised, flooding and CSO will occur at some point. However, even minor reductions in urban flooding and CSO discharge can result in significant reduction in material damage and environmental impact.



By the use of active control, the environmental impact from CSOs etc. can be reduced as well as flooding. Vezzaro et al. (2014) and Vezzaro and Grum (2014) demonstrated a RTC system, where the optimization of the system were based on a virtual cost of CSO discharge. Each CSO were assigned a virtual cost corresponding to the environmental impact. Based on these costs, the total cost of the system could be minimised. By the use of this methodology, integrated modelling, and real-time measurements of recipient states, drainage systems states and precipitation, it will be possible to minimise both urban flooding and environmental impact in future.

Accurate, reliable and integrated analyses and RTC of distributed urban drainage systems requires access to high spatiotemporal resolution rainfall data, which represents the actual spatiotemporal variability of the rainfall over the catchments. Furthermore, analyses and RTC also requires access to high quality in-situ runoff measurements to quantify the system responds during the stormwater event. However, most importantly, there should be a clear and consistent relation between rainfall and runoff.

High spatiotemporal resolution rainfall data can be obtained from weather radar. However, discrepancies between radar predicted rainfall-runoff and measured rainfall-runoff are often observed when weather radar data is applied for urban drainage applications. To minimise these discrepancies weather radar data is often adjusted to ground observations in the form of rain gauges. Unfortunately, discrepancies between predicted rainfall-runoff and measured rainfall-runoff often still occur.

Reliable and accurate in-situ runoff sensors already exist in many urban drainage systems today. To minimise the discrepancies between radar predicted rainfall-runoff and measured rainfall-runoff, it may be beneficial to adjust weather radar rainfall estimates to runoff measurements in the given catchment. Hence, process and model uncertainties related to both rainfall and runoff process are included into the adjusted radar rainfall estimate to improve the accuracy of predicted flow and water levels. Consequently, the adjusted radar-rainfall will be runoff model and catchment specific.

Even though reliable and accurate runoff sensors already exist in many urban drainage systems today, these sensors are often placed at the WWTP. It can be very challenging to close the rainfall-runoff mass-balance for complex combined sewer catchments because of CSO, basins, pumps, etc. To use a runoff based weather radar adjustment concept it is necessary to account for these effects to ensure a close rainfall-runoff mass-balance. A closed rainfall-runoff mass-balance will also potentially improve RTC in itself since all flow sources are accounted for.



## CHAPTER 3. URBAN HYDROLOGY, RAINFALL MEASUREMENT AND RUNOFF MEASUREMENT

An introduction to urban hydrology, rainfall measurement, and runoff measurement is given through this chapter to clarify the scientific context of this thesis. This chapter is used to elaborate the advantages and challenges of using weather radar data for urban applications briefly mentioned in previous chapters. This chapter forms the scientific background for the runoff based weather radar adjustment concept described following chapters.

The natural water cycle is changed significantly when a rural area is urbanised. The differences between rural and urban water cycles are illustrated in Figure 2.

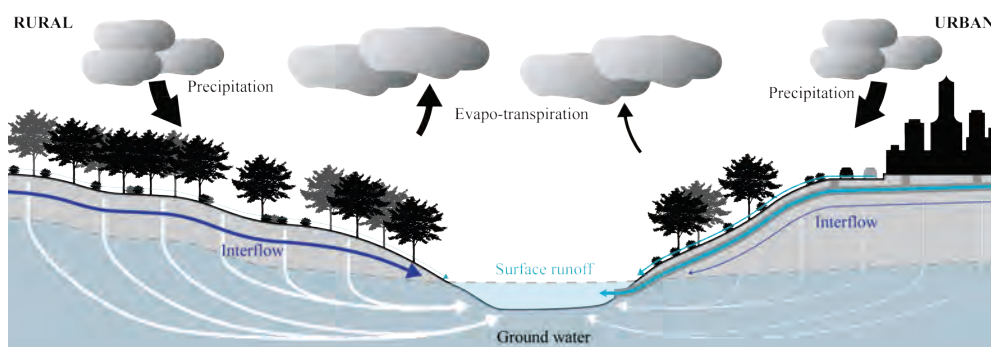


Figure 2: Illustration of rural and urban water cycles. The rural water cycle is dominated by evapo-transpiration, interflow and groundwater flow. When an area have been urbanised, surface runoff increases significantly while evapo-transpiration and infiltration are decreased. The arrow sizes indicates the water cycle distributions.

Urban hydrology is significantly different from rural hydrology. Urban drainage systems typically have a significantly faster runoff response (minutes-hours) compared to a rural system (days). Furthermore, transport paths are highly depended on the layout of the drainage systems. As described in the previous sections, the layout of larger urban drainage systems is a result of decades of continuous construction, expansion and renovation. Runoff from neighbouring catchments may have significantly different routes through the system. Consequently, accurate representation of the rainfalls spatiotemporal variability near the surface of the catchments are needed for analyses and RTC of distributed urban drainage systems (Schilling, 1991; Johann and Verworn, 1997; Berne et al., 2004; Einfalt et al., 2004).

Traditionally, urban hydrologist have relied on precipitation measurements from rain gauges, and Denmark are no different. The first high temporal rain gauges dedicated to urban drainage applications in Denmark were installed in the 1930s. A total of six rain gauges were installed in Gentofte, Odense, Aarhus, Aalborg, Esbjerg and Vejle (WPC, 1974). However, these rain gauges were discontinued in the 1960s. WPC started a Danish national rain gauge network based on Tipping Bucket Rain Gauges (TBRG) in 1979.

Today, TBRG are the most commonly used rain gauge type (Strangeways, 2010). The measuring principle of a TBRG is simple compared to weather radars. Figure 3 shows the TBRG type used in WPCs rain gauge network. The rain gauges consist of a cylinder with an inner diameter of  $203\pm 0.2$  mm ( $\sim 324$  cm<sup>2</sup>) fitted with a funnel which lead the precipitation down to a tipping bucket. Each time the tipping bucket is filled and tips the time stamp and 0.2 mm precipitation is registered. The tipping bucket is gold plated to avoid corrosion, hence avoid that water droplets sticks to a corroded surface (Observator Instruments, 2015).



*Figure 3: A Rimco 7499020 tipping bucket rain gauge shown in closed and open state. The last three digits of the model name defines the tipping bucket size, corresponding to 0.2 mm precipitation pr. tip.*

Rain gauges have historically proven their worth in relation to urban drainage, and are generally assumed accurate. However, several studies suggest that rainfall estimates from rain gauges are subject to substantial uncertainties (Neff, 1977; Fankhauser, 1998; Habib et al., 2001; Duchon and Essenberg, 2001; La Barbera et al., 2002; Ciach, 2003; Sieck et al., 2007; Francey et al., 2010; Rodda and Dixon, 2012). The primary uncertainties are related to wind and lee conditions around the rain gauge. Rain gauges in the WPC network are not corrected for wind and lee conditions.

In relation to urban drainage applications where the spatiotemporal rainfall variability is important, it can be challenging to rely solely on rain gauges. Rain gauges are point measurements, and therefore only representative for a limited range. Hence, a dense rain gauge network is needed to properly account for the spatiotemporal variability of the rainfall. Dense rain gauge networks exist, but they are a rarity (e.g. Blumenfeld and Skaggs, 2011; Changnon, 2002; Villarini et al., 2008). Even if, the finances are available to build a dense rain gauge network, it can be very difficult to find suitable locations for the rain gauges in an urban environment due to shielding effects from buildings.

Figure 4 shows the locations of the 157 active rain gauges in the WPC network along with the position of the five weather radars owned and operated by the Danish Meteorological Institute (DMI). All five radars are C-band radars with a detection range of 240 km and a DMI Quantitative Precipitation Estimation (QPE) range of 100 km (Gill et al., 2006). For measurements beyond the range of 100 km, DMI states that the QPE quality is questionable.

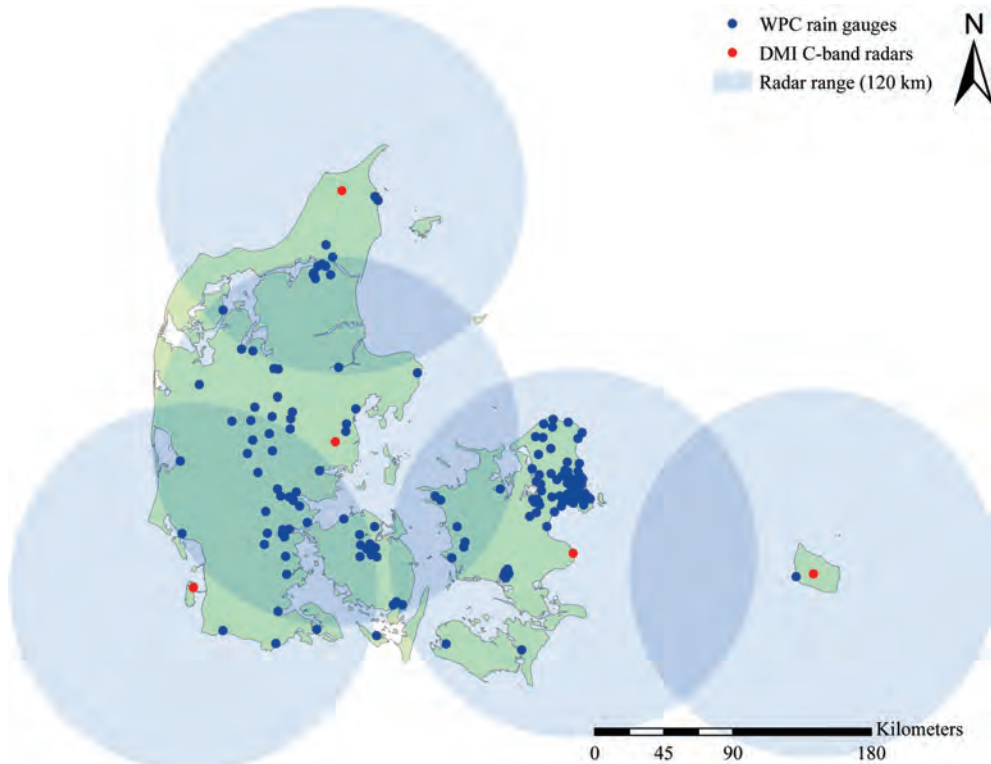


Figure 4: Map of Denmark showing the locations of the 157 active rain gauges in the WPC rain gauge network and the five C-band weather radars operated by DMI. Data are from August 2015.

The density in some areas of Denmark are sufficient to describe the spatiotemporal rainfall variations at scales of several kilometres. For example, the rain gauge density in the area of Copenhagen is approx. one rain gauge pr. 15 km<sup>2</sup>. However, in other parts of the country, the rain gauge density is significantly lower.

Rain gauges have often proven sufficient for urban hydrologist. However, to solve the present challenges in relation to urban flooding and increased environmental standards, an increased interest for high spatiotemporal resolution rainfall data have appear amongst urban hydrologist. The desired spatiotemporal rainfall resolution for urban hydrology is 1km<sup>2</sup> and 1-5 min. (Schilling, 1991; Berne et al., 2004; Einfalt et al., 2004). However, Faurès et al. (1995) have documented cases where a spatial rainfall resolution of 5 ha (~225x225m) are necessary for distributed catchment modelling. Figure 5 illustrates why a high spatiotemporal resolution is needed.

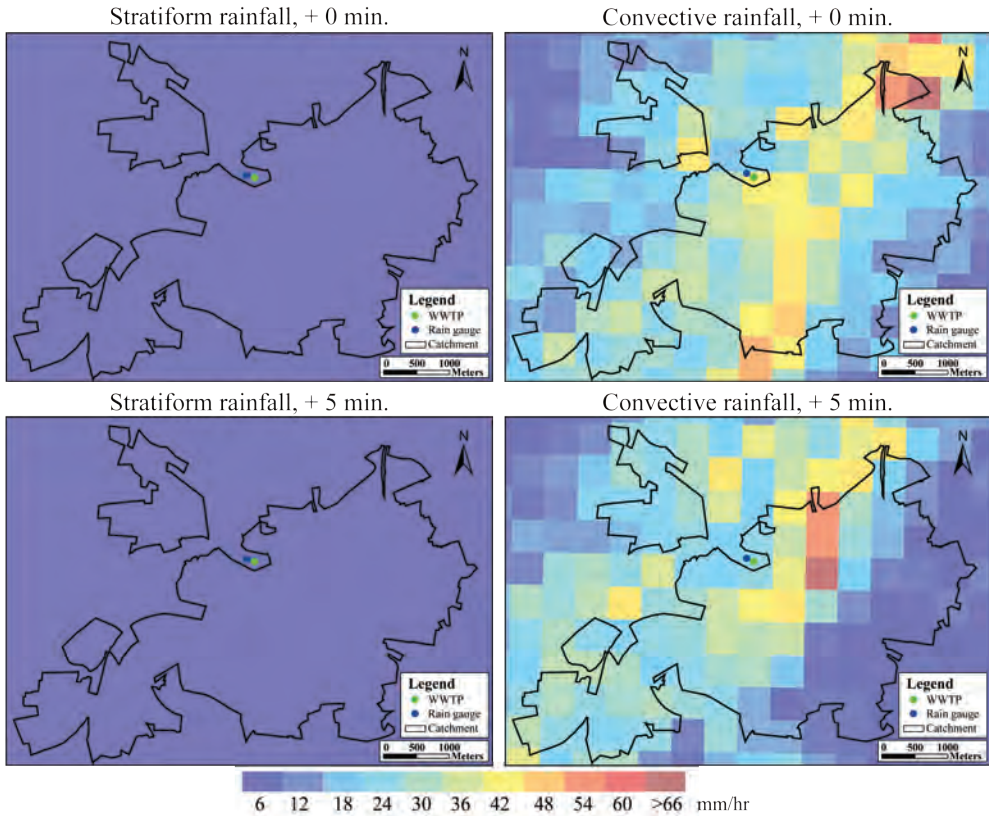


Figure 5: Radar data (500x500m and 5 min.) for a stratiform and convective rainfall event over the Viby catchment (1426 ha), Aarhus, Denmark

Figure 5 illustrates how a stratiform and convective rainfall event evolves over an urban catchment during five minutes. A typical horizontal travel speed for rainfall is in the order of 5-20 m/s. At a velocity of 10 m/s, the movement is 600 m/min, which approximately corresponds to one radar pixel in Figure 5.

A single rain gauge would be enough to probably represent the spatiotemporal rainfall distribution of the stratiform rainfall illustrated in Figure 5. Even for advanced urban drainage applications. However, with a single rain gauge it would not be possible to quantify whether or not the rainfall were evenly distributed over the catchment. To obtain a similar spatiotemporal resolution with rain gauges as the weather radar data has in this example, approx. 80 rain gauges are needed in the catchment (evenly distributed).

The convective rainfall example illustrated in Figure 5 shows how rainfall can vary in time and space. It should be noted, that the rainfall does not only vary in time due to the movement of the precipitation system (NNW movement in this example). The precipitation systems also changes with time due to changes in the rainfall intensities (growth and decay of storm cells). Hence, high spatiotemporal data is necessary to quantify the rainfall over a larger catchment.

Weather radars have some obvious advantages compared to rain gauges. A single weather radar can monitor a large area and detect the spatiotemporal variations of rainfall within this area. Furthermore, a weather radar can measure precipitation in areas where it can be difficult to install rain gauges, e.g. build-up urban areas. On the other hand, rain gauge measurements are direct measurements of the rainfall in a single point near the surface. Weather radar measurements are indirect volumetric scans of the rainfall in the lower atmosphere within a range of up to approx. 250 km (C-band and S-band weather radars).

The measurement principle of weather radars are significantly more complex than the measurement principle of rain gauges. The basic measurement principle of radars is, that the radar emits an electromagnetic pulse into the atmosphere in a given direction and elevation. When the electromagnetic pulse hits something in the atmosphere (a target), a part of the emitted electromagnetic pulse is reflected back towards the radar. The radar then detects the backscattered signal. The measurement principle of weather radars is illustrated in Figure 6.

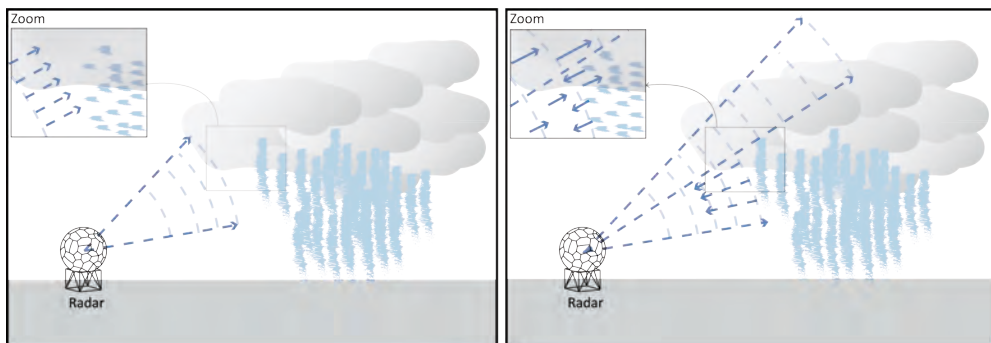


Figure 6: Illustration of how a transmitted electromagnetic pulse from a weather radar is reflected by the water droplets in a precipitation system.

Based on the temporal delay between emitting the electromagnetic pulse and receiving the backscatter of the pulse it is possible to calculate the distance to the target (electromagnetic signals travels with the speed of light). By combining the distance to the target with the direction and elevation of the radar antenna, it is possible to estimate the targets position in the atmosphere. More detailed descriptions of the measurement principle of weather radars can be found in several books (Battan, 1973; Collier, 1996; Doviak and Zrnicek, 2006; Rinehart, 2010).

Due to the complexity of weather radars there exist a number of sources of uncertainties related to radar-based estimation of rainfall at surface level (e.g. AghaKouchak et al., 2010; Austin, 1987; Jordan et al., 2003; Pegram and Clothier, 2001; Rico-Ramirez et al., 2007; Steiner and Smith, 2002; Venkatesan et al., 1997; Wilson and Brandes, 1979). Villarini and Krajewski (2010) have performed an extensive literature review of the main uncertainty sources in single polarization radar-based rainfall estimation. To obtain reliable estimates of the rainfall it is important to understand these uncertainties. To create an overview of the central uncertainties these can be divided into three categories; transmitting radar pulse, reflectivity measurement, and data treatment. The uncertainties related to these three categories are listed in Figure 7.

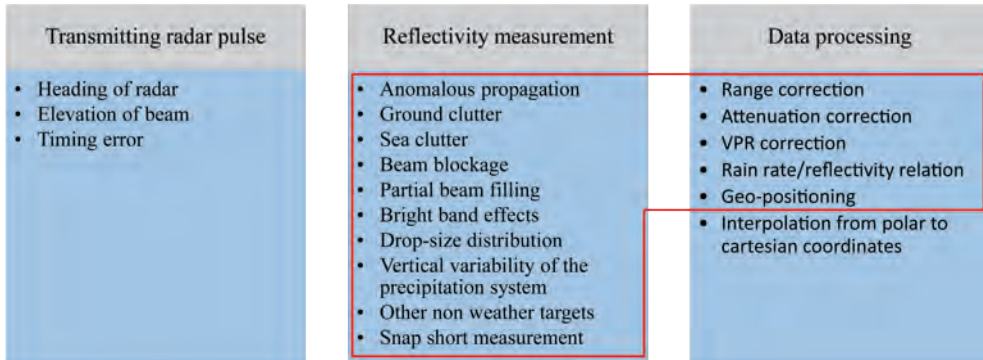


Figure 7: Central sources of uncertainties in radar-based estimation of rainfall using C-band weather radars. The uncertainties related to the points excluded by the red line are possible to control and minimize to the point where they are neglectable. The uncertainties related to the enclosed points are more difficult to control since they can change over time. See description in the following text (Modified after Ahm, 2012).

It is possible to control the uncertainties related to transmitting radar pulse to the point where they are neglectable. The same goes for the point “interpolation from polar to cartesian coordinates (data grids)”. The rest of the uncertainty sources (enclosed by the red line in Figure 7) is more difficult to control since they changes over time. Figure 8 illustrates some of the most common phenomenon’s that affects the reflectivity measurement in the atmosphere.

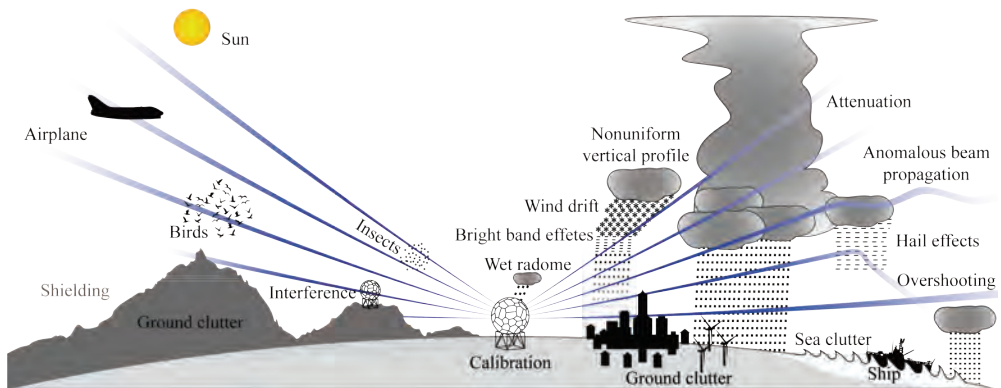


Figure 8: Illustration of the numerous sources in the atmosphere, which may affect the measurement of rainfall reflectivity, and thereby the quality of the radar-based rainfall product (Modified version inspired after Peura et al., 2006).

AghaKouchak et al. (2010) divides the sources of uncertainties (enclosed by the red line in Figure 7) into three error groups; (1) physical errors, (2) inaccuracies in the Z-R relationship, and (3) random errors.

The physical errors are ground clutter, beam blockage, non-meteorological echoes etc. Different algorithms exists to compensate for these errors (e.g. see (Villarini and Krajewski, 2010) for an overview). However, these algorithms are often based on physical assumptions (states) which are unknown. Hence, the corrections performed by these algorithms may not always be valid or correct.



Weather radars does not measure the rainfall intensities directly. It measures the electromagnetic backscatter from the rainfall in the sample volume. The backscatter signal is expressed as the radar reflectivity. The relationship between radar reflectivity ( $Z$ ) [ $mm^6/m^3$ ] and rainfall intensity ( $R$ ) [ $mm/hr$ ] is depended on the actual number and sizes of the droplets in the sample volumes. Hence, the relationship is depended on the drop size distribution (DSD) and drop velocity distribution (DVD). The actual DSD and DVD of the sample volume is rarely known. However, based on ground observations is can be estimated. The unknown and varying DSD and DVD of the rainfall causes inaccuracies in the Z-R relationship.

Traditionally, radar reflectivity is recalculated to rainfall intensities by applying a Z-R relationship based on a two-parameter ( $a$  and  $b$ ) power law function (Marshall and Palmer, 1948; Spilhaus, 1948; Wexler, 1948; Wilson and Brandes, 1979; Fulton et al., 1998):

$$Z = aR^b \rightarrow R = \left(\frac{Z}{a}\right)^{\frac{1}{b}} \quad (1)$$

where  $Z$  is the radar reflectivity [ $mm^6/m^3$ ],  $R$  is the radar rainfall intensity [ $mm/hr$ ], and  $a$  and  $b$  are the power law parameters. Battan (1973) has performed an extensively review of different Z-R relationships (A and B parameters) and classified them by precipitation type. Since the correct DSD and DVD normally is unknown, the general accepted solution is to apply a fixed Z-R relationship and a bias adjustment based on rain gauges (Smith and Krajewski, 1991; Fulton et al., 1998; Seo et al., 1999; Krajewski and Smith, 2002; Borga et al., 2002; Goudenhoofdt and Delobbe, 2009; Thorndahl et al., 2014). Other methods exist as well to minimize the discrepancies between weather radar and rain gauge estimates. These methods are based on principles from data assimilation, uncertainty modelling, probabilistic estimation, ensemble modelling etc. (e.g. AghaKouchak et al., 2010; Bruen and O'Loughlin, 2014; Ciach et al., 2007; Germann et al., 2009; Vogl et al., 2012).

The random errors are the remaining errors after the two first groups of errors have been removed systematically. For hydrological applications, random errors are less important than the systematic errors since the random errors tend to even out in larger hydrological models. It is curial to remove systematic errors (biases). Even small biases in the rainfall estimate can propagate through the hydrological model and result in significant errors in the estimated catchment responses.

The concepts of prediction and nowcasting (forecasting) of flow and water levels in urban drainage systems is a rather unexplored research field. However, during the recent decades this area of research have gained increased attention (Yuan et al., 1999; Pfister and Cassar, 1999; Sempere-Torres et al., 1999; Quirnbach and Schultz, 2002; Tilford et al., 2002; Vieux and Bedient, 2004; Krämer et al., 2007; Achleitner et al., 2009; Liguori et al., 2012; Schellart et al., 2012, 2014; Thorndahl et al., 2013; Goormans and Willems, 2013; Thorndahl and Rasmussen, 2013; Wang et al., 2013; Löwe et al., 2014; Rico-Ramirez et al., 2015). The increased amount of publications during the latest decade might be a result of the increased attention to urban drainage due to urban flooding and climate changes, and the fact, that the quality of the available models have increased significantly. However, the results from the studies are ambiguous, and testifies that further research are needed in these areas.

Traditionally, flow and water level prediction based on radar QPE in urban drainage catchments are performed using the methodology illustrated in Figure 9.

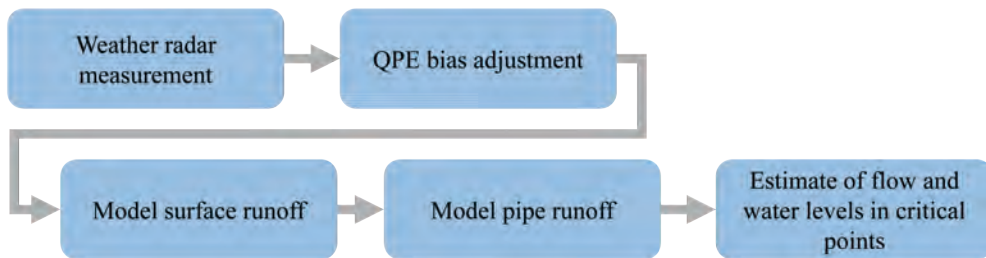


Figure 9: Traditional methodology for flow and water level prediction based on weather radar QPE in urban drainage catchments.

In short (Figure 9): Obtain the best possible weather radar QPE by removing systematic errors such as ground clutter, beam blockage, non-meteorological echoes etc. Adjust QPE to ground level by applying a radar-gauge bias adjustment. The adjusted rainfall estimate is used as input to model surface runoff processes. The estimated surface runoff is used as input to model pipe runoff processes. Based on the modelled pipe runoff, flow and water levels are estimated.

The studies related to prediction of flow and water levels are mainly studies of how radar data performs as rainfall input to urban drainage models compared to rain gauges (Sempere-Torres et al., 1999; Quirnbach and Schultz, 2002; Vieux and Bedient, 2004; Schellart et al., 2012; Goormans and Willems, 2013; Wang et al., 2013). The urban drainage models are based on distributed models. The general conclusions from these studies are that for larger distributed catchments weather radar data result in better prediction of flow and water levels than rain gauges. However, Quirnbach and Schultz (2002) shows, that centrally placed rain gauges in a catchment can outperform weather radar data. They recommend that weather radar data should be used if the distance between rain gauge and catchment is greater than 4 km and if the rain gauge density in the catchment are lower than one rain gauge pr. 16 km<sup>2</sup>. On the contrary, the prediction accuracy for these studies are in the range from 15-20%.

Several authors have explored the potential of using weather radar data to nowcast flow and water levels in urban drainage systems (Pfister and Cassar, 1999; Yuan et al., 1999; Krämer et al., 2007; Achleitner et al., 2009; Liguori et al., 2012; Thorndahl et al., 2013; Thorndahl and Rasmussen, 2013; Löwe et al., 2014; Schellart et al., 2014). The models used are primarily auto-calibrated lumped models that focus on predicting flows in a single critical point. Hence, the runoff model parameters are constantly changed to compensate for discrepancies between prediction and observations.

Common for the studies mentioned above are, that it is difficult to handle and quantify the uncertainties, and how they propagate through the models from radar reflectivity to predicted flow and water levels. Rossa et al. (2011) have performed an extensively review of how uncertainty propagate through advanced hydro-meteorological forecast systems. The review testifies that further research are needed to improve radar QPE for small- and medium-scale catchments, and to quantify uncertainties in all model steps from reflectivity measurement to flow prediction.

Rico-Ramirez et al. (2015) implemented a probabilistic system to model the uncertainty associated to radar QPE and how this uncertainty propagate through the drainage system. The results show, that the ensembles were able to capture the flow peaks for some events, and not for other events. However, in their study, it was the radar QPE which were perturbed. Hence, the uncertainties related to the urban drainage model structure and calibration were not taken into account.

Researches around the world are currently working on methods to quantify and model the uncertainties related to the five steps illustrated in Figure 9. However, it will take several years before it is possible to do this for distributed urban stormwater drainage systems. This thesis investigates the possibility of a shortcut to reliable prediction and nowcasting of flow and water levels in urban drainage systems by adjusting weather radar QPE to runoff measurements.

As described previously, urban hydrologist have relied on rain gauges for many decades to measure rainfall. They have only in recent decades started to adopt weather radar data. However, in most urban catchments a third type of “rainfall sensor” already exist: runoff measurements. Figure 10 illustrates the three different measurement principles, which are available for measuring rainfall in urban drainage catchments.

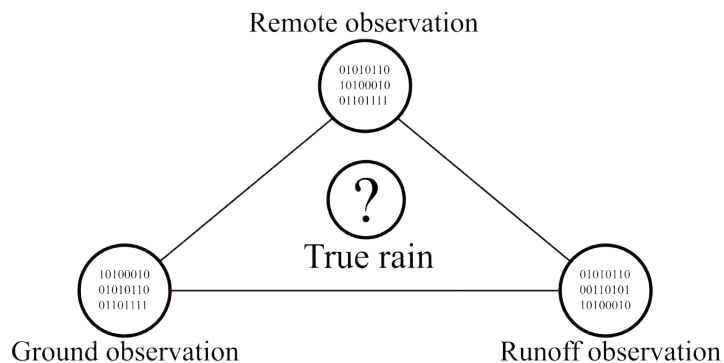


Figure 10: Illustration of the different sensor principles available for measuring rainfall in urban catchments. The ground observations are different types of rain gauges, the remote observations are different types of weather radars (both land and satellite based), and the runoff observations are for example measurements of flow, water level, pump effect, and overflow registrations (Ahm, 2012).

The measurement principles illustrated in Figure 10 all gives qualified estimates of the true rainfall. However, it is important to underline, that the measurements are only estimates of the true rainfall. Hence, an interpretation of the true rainfall, not an exact measurement of the true rainfall. The measurement principles all have their advantages, disadvantages, and limitations. However, if combined correctly, they can all contribute to a more precise estimation of the true rainfall.

The advantages of weather radar measurements are that it is possible to measure the relative spatiotemporal variability of the rainfall over a larger area in the lower atmosphere. However, the accuracy of the relation between radar reflectivity and rainfall intensity is questionable. Rain gauges are able to measure rainfall depths and intensities accurately at ground level in a single point. Runoff observations measures the part of the rainfall, which

actually becomes runoff and affects the stormwater drainage system. On the contrary, runoff measurements are spatiotemporal integrated measurements of the real spatiotemporal rainfall variability over the measurement catchment. Hence, it is challenging to relate the runoff measurements directly to weather radar measurements, and even rain gauge measurements.

As described before, weather radar QPE are traditionally adjusted to rain gauges. However, it make sense to investigate the possible of adjusting weather radar QPE to runoff measurements for urban drainage applications to improve prediction of flow and water levels. Figure 11 illustrates the adjustment methodology investigated in this thesis compared to the traditional adjustment methodology.

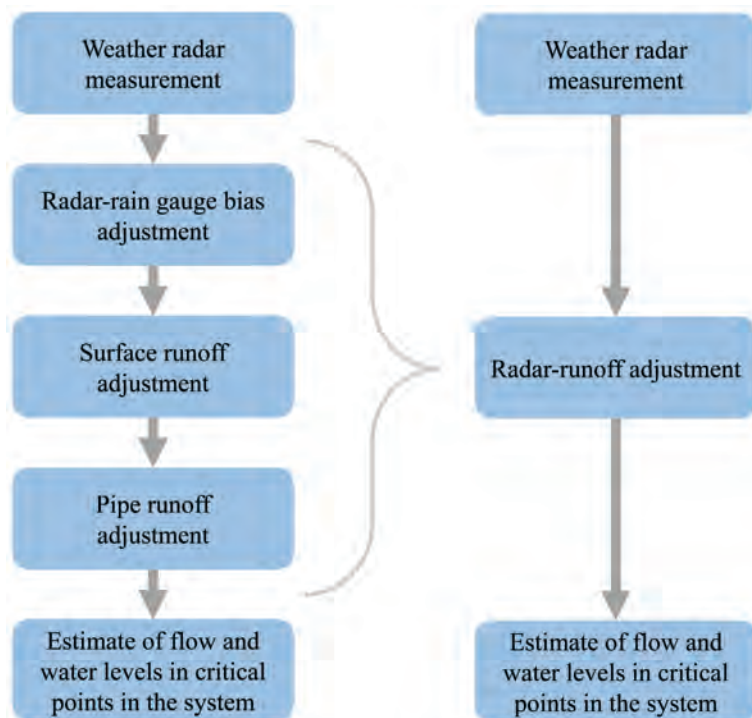


Figure 11: The traditional adjustment methodology for flow and water level prediction based on weather radar QPE in an urban drainage catchments compared with the runoff based adjustment methodology proposed in this thesis.

Instead of the traditional “five step” methodology a simplified “three step” methodology is proposed in thesis to improve flow and water level prediction based on weather radar data. Instead of first adjusting the weather radar QPE to ground observations, and then applying the rainfall data to a runoff model (with all of its own uncertainties) to estimate runoff flows and water levels, the proposed methodology adjust the weather radar QPE to the runoff via the runoff model.

The transfer function between rainfall and runoff are still a runoff model, but in this case, it is interpret as the “true” transfer function. Hence, every uncertainties and discrepancies between rainfall and runoff are incorporated into the rainfall estimate. The hypothesis is that

this will improve prediction of flow and water levels. However, the downside is that the weather radar QPE will be catchment and runoff model specific.

The idea of adjusting weather radar QPE using runoff measurements is not novel in itself Marx et al. (2006) estimated Z-R relationships for large rural catchments in a mountainous area using inverse hydrological modelling. The catchment sizes ranged from 43.5 to 601 km<sup>2</sup> and the temporal data resolution was one hour. Rainfall-runoff hydrographs from rural catchments of these sizes are very long (several days) and smoothed compared to rainfall-runoff hydrographs from urban drainage catchments (minutes). The novelty of this Ph.D. study is to apply this idea in an urban drainage context on small-scale rapid reacting catchments with all of its complexity. High-quality rainfall and rainfall-runoff data are required to account for the rapid changes in urban drainage systems during rainfall compared to large rural areas.

Runoff measurements are also associated with uncertainties as rain gauge and weather radar measurements. The relative uncertainties specified by manufacturers are usually below 1%. However, to obtain the manufactures specifications regarding accuracy, the sensors must be installed under ideal measurement conditions. Ideal conditions are a rarity due to the harsh environment in sewers and their typical layouts. Sewers are constructed to effectively convey water, not for optimal measurement conditions. Nevertheless, flow measurements in sewers have been extensively used by several authors (Bertrand-Krajewski et al., 1995, 2000a; Schaarup-Jensen, 1998; Berthier, 1999; Maheepala et al., 2001; Francey et al., 2010; Sandoval et al., 2014).

The actual relative uncertainties under controlled conditions for flow measurements are in the range 2-20% (Bertrand-Krajewski et al., 2003; Hoppe et al., 2009). However, in-situ flow sensors are often installed where practical conditions permit. Combined with cultural traditions of minimum calibration and verification, flow rates in sewers are frequently known with an (in)accuracy of  $\pm 50\%$  to  $\pm 100\%$  (Bertrand-Krajewski et al., 2000b). To use a runoff based weather radar adjustment, the uncertainties of the runoff measurements have to be handled to some extent.

It is important to underline, that the approach of this thesis is not to investigate if one should invest in either rain gauges or runoff-sensors as the adjustment basis for weather radars. The question is:

“Is it possible utilise already existing sensors in stormwater drainage systems to improve weather radar adjustment for urban drainage applications?”

If it is possible, then the amount of available adjustment sensors would significantly increase since in-situ runoff sensors typically are available in urban drainage catchments.

A summary of the scientific outcome of this Ph.D. project is given in chapter 5 on the bases of the six supporting papers. Chapter 6 provides the conclusion of this Ph.D. project. However, before the scientific outcome is summarised, a description of the two case study areas used to investigate the research objectives of this Ph.D. is given in the following chapter. All six supporting papers are based on one of these two case study areas.



## CHAPTER 4. CASE STUDY AREAS

Two different case study areas have been used to investigate the research objectives of this Ph.D. project. A small well-defined urban catchment for development of radar-runoff adjustment methods, and a larger complex urban catchment to test the methods under real practical conditions. The small catchment is entitled *BEWARE* and the larger catchment is entitled *Viby*. The locations of these catchments are shown in Figure 12 together with the locations of the rain gauges in WPC’s network and the locations of the weather radars in DMI’s network. Both networks have been briefly described in the previous chapter.

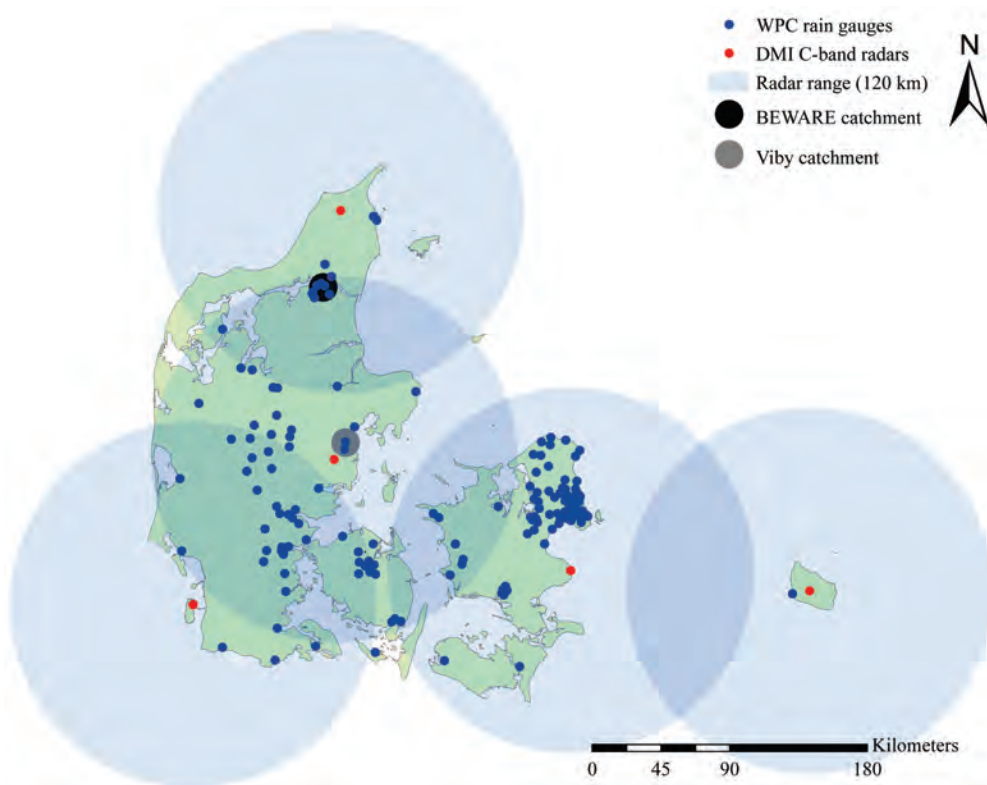


Figure 12: Map of Denmark showing the locations of the two case study areas along with the active WPC rain gauges and DMI weather radars. Data obtained August 2015.

An overview of the two case study areas are given in the following sections. Detailed descriptions of the catchments and sensors are given in the supporting papers for this thesis.

### 4.1. SMALL WELL-DEFINED URBAN CATCHMENT (BEWARE)

The small well-defined urban catchment is a measurement station located in the central part of Aalborg, Denmark, and was created as a part of the Ph.D. study. Aalborg is the fourth largest city in Denmark with a population of 104,855 (DST, 2012). The measurement station is entitled “BEWARE” (Buildings as an intElligent WATER Resource) and was designed for multiple purposes. The main objectives for creating the measurement station was to study the

correlations between rainfall and runoff at small-scale with a minimum of uncertainties, and to study how elevated imperiously surfaces in the urban environment can be utilised for rainwater harvesting. It is therefore, equipment with sensors to measure rainfall intensities, runoff flows and some water quality properties. However, it is only the first objective, which is related to this Ph.D. project. Figure 13 shows an Orthophoto of the measurement station and Figure 14 shows a panoramic photo of the upper-level.



Figure 13: Orthophoto of the measurement station (line hatching), and the subdivision of the upper level of the car-park structure into two areas (dashed line). The north-westerly part represent the BEWARE catchment. DDO© Copyright COWI (2015).



Figure 14: Panoramic photo of the upper-level of the measurement station, BEWARE. The photo is taken from the norther corner of the catchment (April 2014).

The monitoring station is installed in a three-level car-parking structure with a simple layout, which makes it very suitable for a combined rainfall and runoff measurement station. The upper level is an impermeable concrete surface of approx. 2900 m<sup>3</sup>. The runoff is drained via an exposed drainage system beneath the upper-level and collected in two downpipes. The drainage system separate the upper-level in two catchments (marked with the dashed line in



Figure 13). It was chosen to only monitor the runoff from the north-westerly part, which result in a catchment area of 1395 m<sup>3</sup>. Further details on the development and setup of the measurement station are given by Ahm and Rasmussen (2015a). Figure 15 shows a perspective illustration of the parking structure and measurement systems.

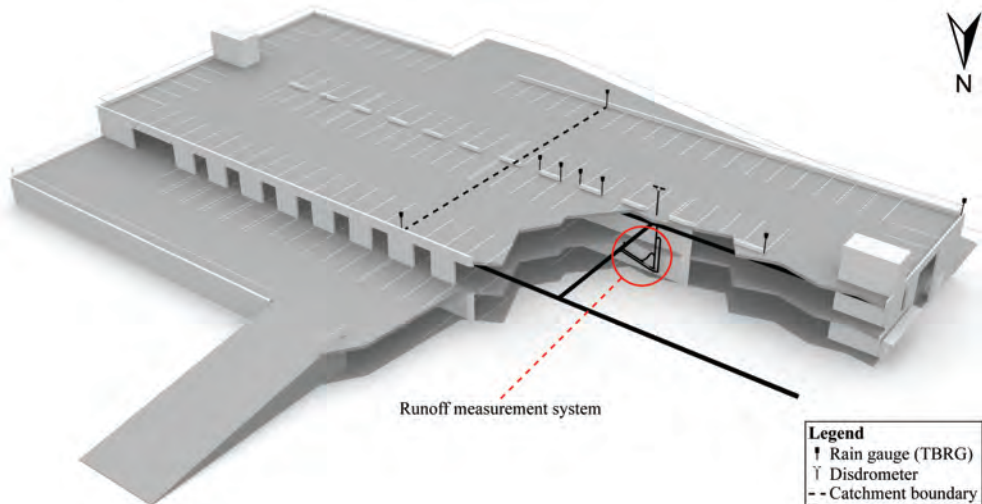


Figure 15: Perspective illustration of BEWARE seen from north showing the location of the different measurement instruments. The rain gauge located in the norther corner of the catchment is not visible due to the cropped view of the building (Modified after Ahm and Rasmussen, 2015a).

The runoff measurement system and disdrometer have been operational since March and April 2013, respectively. The runoff measurement systems consist of multiple sensors to measure the runoff accurately over a wide flow regime. The final runoff measurement system is shown in Figure 16.



Figure 16: The runoff measurement system with heating cables, insulation and collision protection.

The nine tipping bucket rain gauges (TBRG) were installed during the summer and autumn of 2013. The first six have been operation since July 2013 and the remaining three have been operational since November 2013. Figure 17 shows three photos of the catchments during wet and dry weather, and some of the rainfall sensors placed on the centreline of the catchment.



*Figure 17: Photos from the BEWARE catchment and some of the rainfall sensors (April 2014). The left picture is taken in dry weather from the center of the catchment towards south-east. The upper right photo is taken during wet weather from the center of the catchment towards south-west. The lower right is taken during dry weather from the south-easterly side.*

Due to the layout of the drainage system and prefabricated concrete elements, the catchment is naturally divided in 64 subcatchment with their own drainage point. A drainage point is shown the in Figure 17 (left photo). Ahm and Rasmussen (2015b) gives a more detailed description of the drainage system layout and transfer model used between rainfall and runoff (surface and pipe runoff model).

In the period March 2013 to December 2015, more than 300 Precipitation events larger than 1 mm have been recorded. The uptime of the measurement systems have been around 99% during this period. All data can be viewed online at <http://www.vejrradar.dk/beware>.

Beside the sensors located at BEWARE, ground and remote observations exist in the area around the catchment; a weather radar and 11 rain gauges. The rain gauges are a part of the WPC rain gauge network and the weather radar is a part of DMI's weather radar network. Both networks are described in Chapter 1 (Figure 4). The WPC rain gauges have not been

used in any of the supporting papers for this thesis. It is planned to include them in a future study of radar and rain gauge representativeness in relation to urban drainage rainfall-runoff. The locations of the WPC rain gauges and the Verring weather radar are shown in Figure 18 in relation to BEWARE.

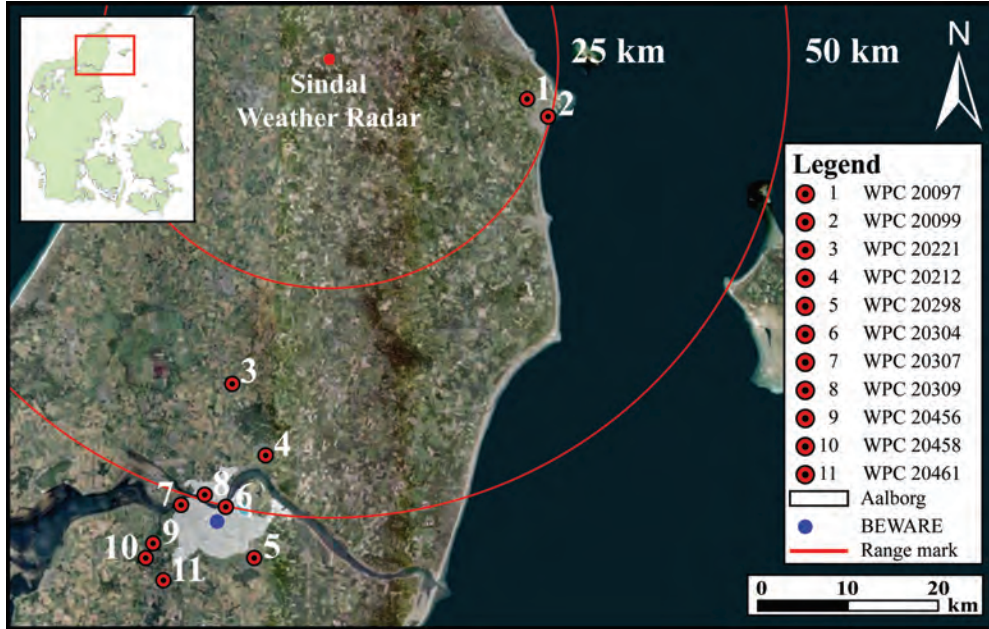


Figure 18: Orthophoto showing the location of Aalborg, BEWARE, Sindal weather radar and 11 WPC rain gauges. DDO© Copyright COWI (2015).

The Sindal weather radar is located approx. 52 km north of BEWARE. The radar is a 250 kW single-polarization Doppler C-band weather radar produced by Enterprise Electronics Corporation (EEC). By the use of the Doppler Effect it is possible to determine the radial velocity of all targets detected by the radar. This can for example be used to identify ground clutter targets since they are sedentary. The radar and scanning settings of the Sindal weather radar are listed in Table 1.

Table 1: Operational parameters settings for the Sindal weather radar and the Verring weather radar (Overgaard, 2010). The Verring weather radar is described further in section 4.2.

Radar parameter	Reflectivity scan settings	Doppler scan settings
Radar frequency	5.625 Ghz	5.625 Ghz
Radar peak	275 kW	275 kW
Pulse length	0.8 $\mu$ s	0.8 $\mu$ s
Detection range	240 km	120 km
Gate size (bin length)	500 m	500 m
Angular resolution	1 deg.	1 deg.
Radar rotational rate	20 deg./s	20 deg./s
Pulse repetition frequency	225 Hz	885/1180 Hz
Scan elevation angles (in deg.)	0.5, 0.7, 1.0, 1.5, 2.4, 4.5, 8.5, 13.0, 15.0	0.7, 1.0, 1.5, 2.4, 4.5, 8.5, 13.0, 89.0

The Sindal radar perform a scan cycle every five minutes. At the minutes 00, 10, 20, 30, 40, and 50 the radar starts a full range non-Doppler scan cycle, entitled reflectivity scans. At the minutes 5, 15, 25, 35, 45, and 55 the radar starts a reduced range Doppler scan cycle, entitled Doppler scans (Overgaard, 2010).

The Sindal weather radar is located on a hilltop and the general terrain slope towards BEWARE is downhill and flat as shown in Figure 19. The elevation of the radar antenna is approx. 140 m above sea level. The ground elevation at BEWARE is 6 m above sea level. Fields and smaller villages dominate the landscape between the radar and the catchment.

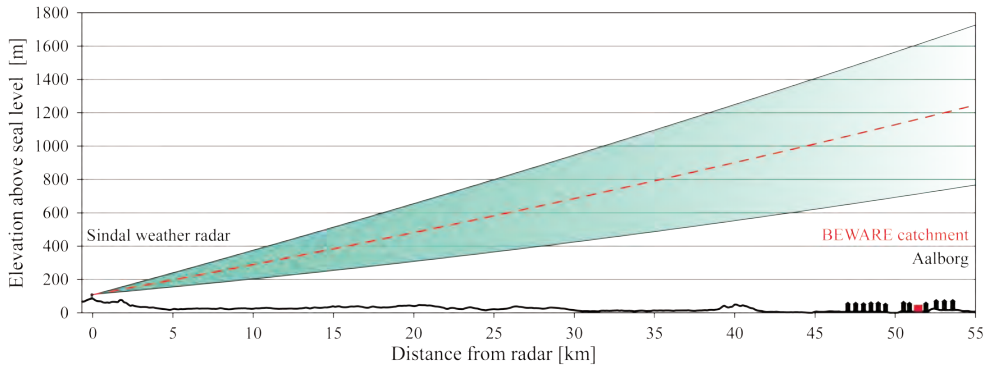


Figure 19: Terrain profile between the Sindal weather radar and BEWARE shown together with the radar beam propagation under normal atmospheric conditions for a scan elevation of  $1^\circ$ .

Beside the terrain profile, Figure 19 also show the radar beam propagation under normal atmospheric conditions for a scan elevation of  $1^\circ$ . At a range of 52 km the elevation for the beam is approx. 723 m, 1177 m and 1630 m for the bottom, centerline and top of the beam, respectively. During sub-refraction and super-refraction conditions, the elevation of the radar beam would be slightly lower and higher, respectively.  $\pm 25$  m over BEWARE for the  $1^\circ$  scan elevation.

Due to the terrain profile, the amount of ground clutter should be minimal during sub, standard and super-refraction atmospheric condition. However, overshooting, bright band, vertical rainfall profile, and wind-drift effects may have a negative effect on the quality of the weather radar measurements over BEWARE due to the measurement elevation.

This case study area were used for the following studies: (Ahm and Rasmussen, 2015a, 2015b). More detailed descriptions of sensors and data are given in these papers.

## 4.2. LARGER COMPLEX URBAN CATCHMENT (VIBY)

The larger case study area used in this Ph.D. project is located in the municipality of Aarhus, Denmark. Aarhus is the second largest city in Denmark with a population of 252,213 (DST, 2012). The catchment coverage is shown in Figure 20 and covers five areas; Hasselager, Holme, Kolt, Stavtrup and Viby. The combination of these five areas will be referred to as the Viby catchment.

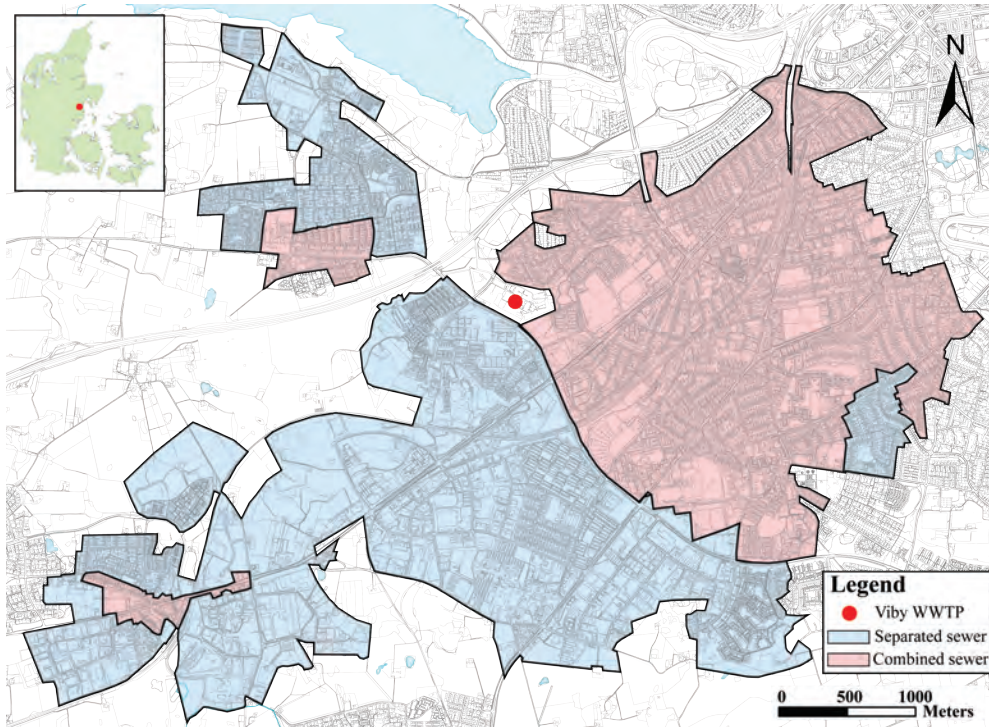


Figure 20: Case study area, Viby Catchment, located in the municipality of Aarhus, Denmark (Modified after Ahm et al., 2013).

The size of the Viby catchment is 1426 ha consisting of 678 ha combined sewers and 748 ha separated sewers. The dry weather load to Viby WWTP is approx. 53,250 PE (person equivalent) (Brodersen, 2012). The runoff is only measured for the part of the catchment, which have combined sewers. The impervious fractions of each subcatchment have been estimated on available GIS data (Aarhus Vand A/S, 2012). The area-weighted average of the impervious fraction of the part of the catchment, which have combined sewers, is 38.78%.

Viby WWTP receive water from multiple catchments; Harlev, Hasselager, Holme, Kolt, Stavtrup, Viby and Aaby. The sewer systems types of these catchments and how the water is conveyed to Viby WWTP are listed in Table 2.

Table 2: Overview of the catchments connected to Viby WWTP.

Catchment	Conveyance to Viby WWTP	Sewer system type
Harlev	Pumpline	Partial separated (ongoing)
Hasselager	Gravity	Partial separated (ongoing)
Holme	Gravity	Partial separated (ongoing)
Kolt	Gravity	Separated
Stavtrup	Pumpline	Separated
Viby	Gravity	Combined
Aaby	Pumpline (excess water during wet weather)	Combined

Harlev and Aaby are connected to Viby WWTP via pumphines. The pumpline from Aaby is primarily used for excess water during wet weather. An overview of how the catchments are connect to the inlet to Viby WWTP are shown in Figure 21.

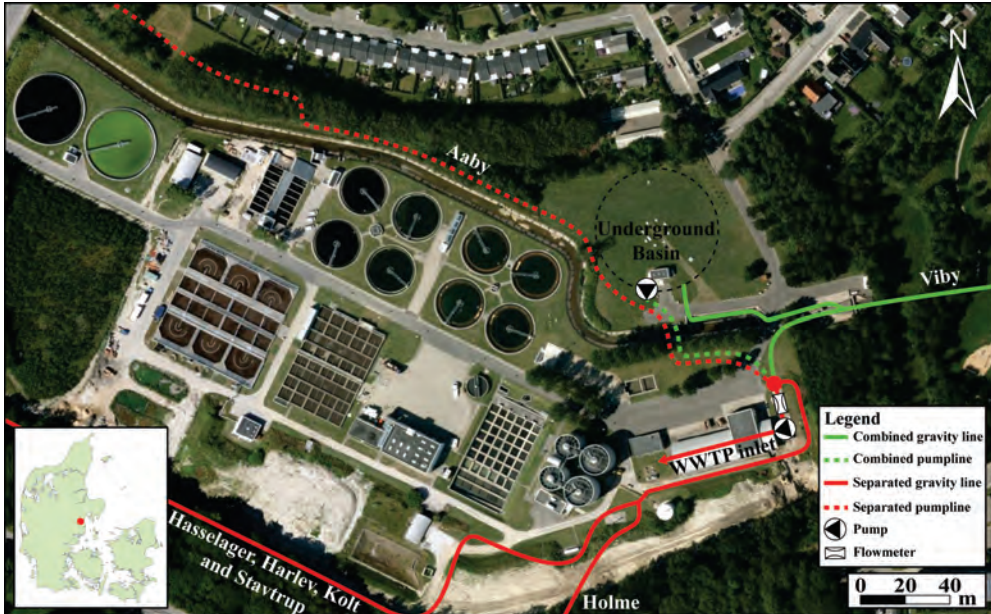


Figure 21: Orthophoto of Viby WWTP with illustrations of how the sewers from the catchments are connect to the WWTP. DDO© Copyright COWI (2015).

The hydraulic wet weather capacity of Viby WWTP is 1.26 m<sup>3</sup>/s. When larger flows occur, excess water is discharged via an internal overflow to the underground basin. The excess water is stored in the underground basin until there is available capacity at the WWTP again. When capacity is available at the WWTP, the stored water is pumped back to the WWTP. In cases where the basin capacity is insufficient, a CSO will take place via an external overflow structure to the nearby stream.

The underground basin has been operational since September 2011 to minimize the number of CSO events from Viby WWTP. The capacity of the new underground basin is approx. 16,000 m<sup>3</sup>, which corresponds to a rainfall depth of approx. 10 mm (runoff contributing area approx. 160 ha). Aarhus Vand A/S (water utility company) has reduced the number of CSO's at Viby WWTP from almost every time it rained to a few times each year with the construction of the new basin.

To reduce peak flows from the Viby catchment, basins of varying sizes (165 m<sup>3</sup> to 11000 m<sup>3</sup>) exist distributed in the catchment. The capacity of these basins corresponds to rainfall depths varying from 11.6 mm to 188.6 mm for the given subcatchments. As a result, the numbers of CSO events in the catchment is almost non-existing. If a CSO event occur, it will likely occur at the WWTP to the underground basin.

With the construction of the underground basin, this catchment offers a unique opportunity to close the rainfall-runoff mass-balance during heavy rainfall where CSO normally occur. Usually, CSO discharge volumes are no measured. At Viby WWTP, the volume discharged is measured via electromagnetic flow meters when it is pumped back to the WWTP from the basin. Figure 22 shows the CSO structures and the underground basin at Viby WWTP.

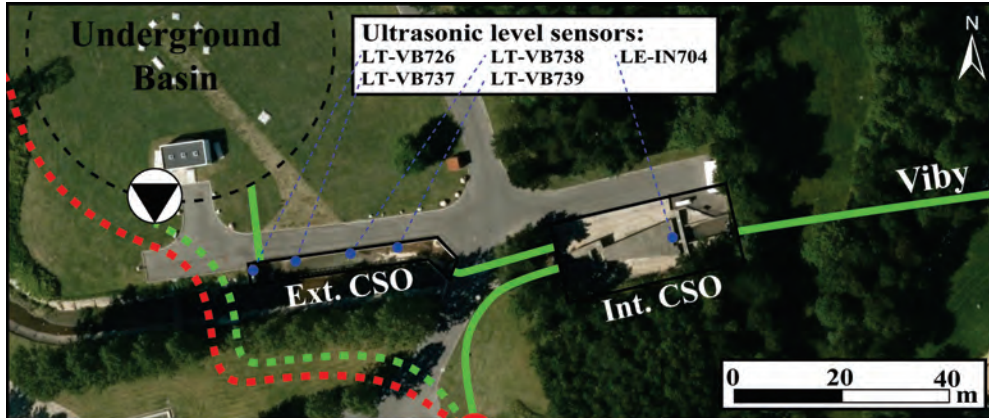


Figure 22: Orthophoto of the overflow structures near to the Viby WWTP. The overview shows the internal CSO structure, the underground basin and the external CSO structure. Furthermore, it shows the available water level sensors in the two overflow structures. DDO© Copyright COWI (2015).

The internal CSO structure were built in 1963, but have been reconstructed several times since. It is a complex double-sided weir with two different overflow levels and grating. At low discharge flows, the discharge flows through grating and over an angled sharp crested weir. At high discharge flows, the discharge also flows over concrete wall, which can be defined as a broad crested weir at low overflow heights. At large overflow heights, it may act as a sharp crested weir. The two lower weirs are approx. 18.7 m in total. The two upper weirs are approx. 37 m in total. Figure 23 shows the internal CSO during dry and wet weather. The weather situation shown in Figure 23 is during heavy rainfall the 27/07-2013. The accumulated rainfall depth this day was approx. 22 mm with peak intensities over 100 mm/hr.



Figure 23: Photo of the internal CSO during dry and wet weather. The photos are taken from the northerly side of overflow structure towards west and east, respectively. The overflow structure are symmetric along the centreline of the inflow channel.

The external CSO was built at the same time as the underground basin. The external CSO can be defined as an ideal broad crested weir with a total length of approx. 39.5 m. Figure 24 shows the external CSO during dry and wet weather. The weather situation shown in Figure 24 is during a three-day long-duration rainfall and snow melting the 17/01-2014. The accumulated rainfall depth during these three days (16-18/01) was approx. 35 mm. At the time the photo was taken, the accumulated rainfall depth was approx. 19 mm.



Figure 24: Photo of the external CSO during dry and weather. The photos are taken from the westerly and south-easterly sides of the overflow structure, respectively.

Ultrasonic water level sensors monitor both the internal and external CSO. Figure 22 shows the position of the sensors. In addition to the five water levels sensors monitoring the overflow structures, basin level and pump flows are also monitored. Figure 25 illustrates the locations of the available hydraulic sensors.

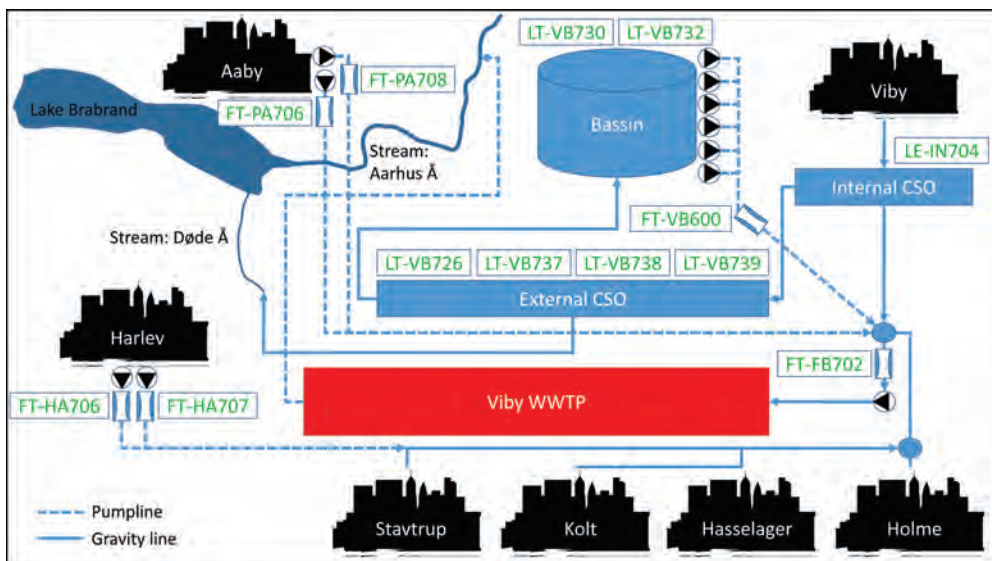


Figure 25: Schematic overview of the available hydraulic sensors. The sensors are stated with their internal reference names. Reference abbreviations: FT: Flow Transmitter, LT and LE: Level Transmitter, VB: Viby Basin, IN: Inlet, FB: Pre-treatment, PA: Pump station Aaby and HA: Harlev.

An electromagnetic flow meter is mounted after each of the six pumps: FT-VB711, FT-VB712, FT-VB713, FT-VB714, FT-VB715 and FT-VB716. The sum of these six flow measurements are aggregate to the sensor FT-VB600. All the hydraulic sensors shown in Figure 25 are logged with a temporal resolution of one minute. An overview of the sensor types and their accuracy is given in Table 3.



Table 3: Overview of the available hydraulic sensors (VEGA Grieshaber, 2005; Siemens Milltronics Process Instruments, 2008; Siemens Flow Instruments, 2010a, 2010b; Ørum and Jensen Elektronik, 2015). The sensor principle is stated in parentheses after the sensor type. Abbreviations: US: Ultrasonic, P: Pressure, EM: Electromagnetic, FS: Full Scale (measurement range) and MV: Measured Value.

Reference	Sensor type	Manufacture/product	Accuracy
LE-IN704	Level (US)	VEGASON 61	$\pm 10$ mm
LT-VB726	Level (US)	Siemens SITRANS Probe LU	$\pm 0,15\%$ FS (6 m)
LT-VB730	Level (P)	Ørum og Jensen SH3102	$\pm 0,25\%$ FS (10m)
LT-VB732	Level (P)	Ørum og Jensen SH3102	$\pm 0,25\%$ FS (10m)
LT-VB737	Level (US)	Siemens SITRANS Probe LU	$\pm 0,15\%$ FS (6 m)
LT-VB738	Level (US)	Siemens SITRANS Probe LU	$\pm 0,15\%$ FS (6 m)
LT-VB739	Level (US)	Siemens SITRANS Probe LU	$\pm 0,15\%$ FS (6 m)
FT-VB600	Flow (EM)	Siemens MagFlo 6000	$V < 0,1$ m/s $\pm 0,25\%$ MV
FT-FB702	Flow (EM)	Siemens MagFlo 6000	$V < 0,1$ m/s $\pm 0,25\%$ MV
FT-PA706	Flow (EM)	Siemens MagFlo 6000	$V < 0,1$ m/s $\pm 0,25\%$ MV
FT-PA708	Flow (EM)	Siemens MagFlo 6000	$V < 0,1$ m/s $\pm 0,25\%$ MV
FT-HA706	Flow (EM)	MJK MAGFLUX 7200	$V < 0,1$ m/s $\pm 0,25\%$ MV
FT-HA707	Flow (EM)	MJK MAGFLUX 7200	$V < 0,1$ m/s $\pm 0,25\%$ MV

The accuracy of the electromagnetic flow meters are measured under ideal conditions in a laboratory. Experience with the accuracy of inductive flow measurement from sewers are in the range of 2–4% (Bertrand-Krajewski et al., 2003; Hoppe et al., 2009). These larger uncertainties can be caused varying temperature, density and particles in the fluid.

Beside the runoff sensors, ground and remote observations also exist for the Viby catchment; a weather radar and three rain gauges. The rain gauges are a part of the WPC rain gauge network and the weather radar is a part of DMI's weather radar network. Both networks are described in chapter 2 (Figure 4). Figure 26 shows the locations of the three WPC rain gauges and the Verring weather radar in relation to the Viby catchment.

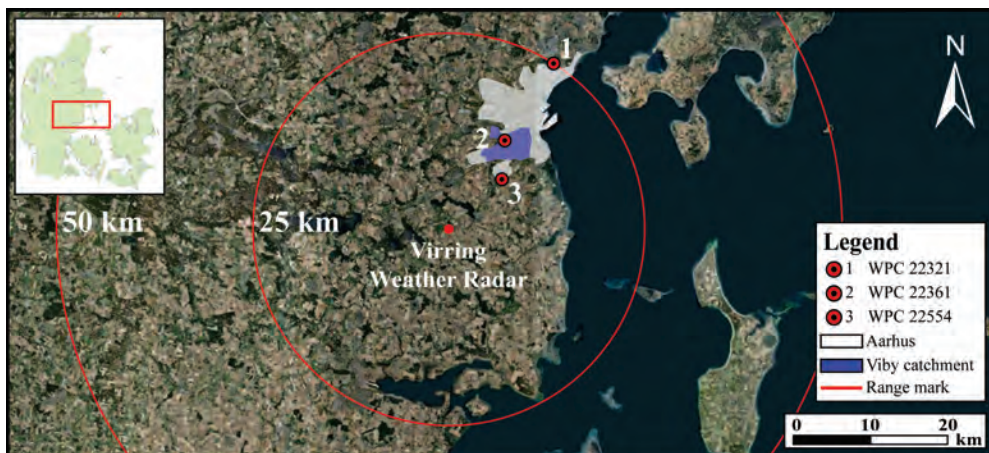


Figure 26: Orthophoto of Aarhus and the Viby Catchment showing the location of Verring weather radar and three WPC rain gauges in the proximity of the Viby catchment. DDO© Copyright COWI (2015).

The Verring weather radar is located approx. 13.5 km southwest of Viby WWTP. The radar is a 250 kW dual-polarization Doppler C-band weather radar (DWSR-2500C) produced

by EEC. By the use of the Doppler Effect it is possible to determine the radial velocity of all targets detected by the radar. This can for example be used to identify ground clutter targets since they are sedentary. Dual-polarization means that the transmitted electromagnetic pulse is polarized both horizontally and vertically in respect to the ground. The dual-polarization give information about the precipitations shape which makes is possible to classify the precipitation type. This information were not available for the studies performed during this Ph.D. study. The radar and scanning settings of the Verring weather radar are listed in Table 1. The scan cycles of the Verring weather radar are similar to the Sindal weather radar described in section 4.1.

The Verring weather radar is located on a hilltop and the general terrain slope towards the Viby catchment is downhill as shown in Figure 27. The elevation of the radar antenna is approx. 140 m above sea level. The elevation of the Viby catchment ranges from 5-75 m above sea level. Fields and smaller villages dominate the landscape between the radar and the catchment.

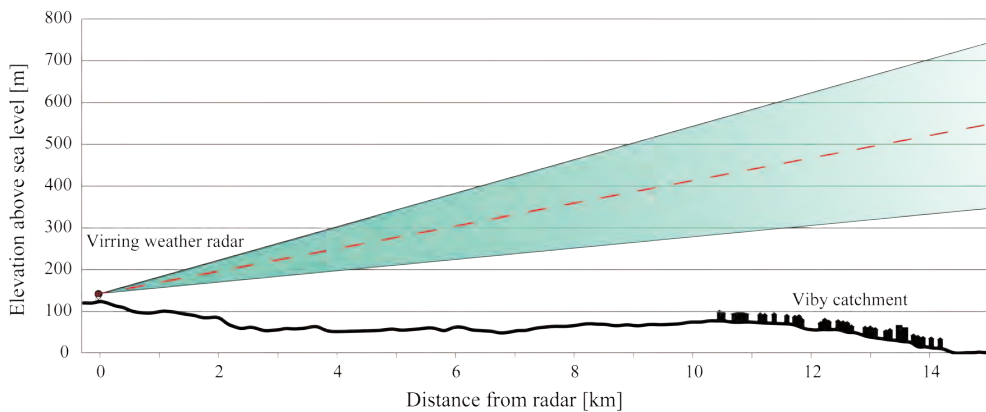


Figure 27: Terrain profile between the Verring weather radar and the Viby catchment shown together with the radar beam propagation under normal atmospheric conditions for a scan elevation of 1°.

Beside the terrain profile, Figure 27 also show the radar beam propagation under normal atmospheric conditions (standard refraction) for a scan elevation of 1°. At a range of 13.5 km the elevation for the beam is approx. 268 m, 386 m, and 504 m for the bottom, centerline and top of the beam, respectively. During sub-refraction and super-refraction conditions, the elevation of the radar beam would be slightly lower and higher, respectively.  $\pm 2$  m over the Viby catchment for the 1° scan elevation.

Due to the terrain profile the amount of ground clutter should be minimal during sub, standard and super-refraction atmospheric condition. Furthermore, overshooting, bright band, vertical rainfall profile, and wind drift effects should be minimal due to the low measurement elevation over the catchment.

This case study area have been used in the following studies: (Ahm et al., 2013, 2016a, 2016b, 2016c). More detailed descriptions of sensors and data are given in these articles.

# CHAPTER 5. RAINFALL-RUNOFF BASED WEATHER RADAR ADJUSTMENT

The basic principle of the rainfall-runoff based weather radar adjustment approach was illustrated in Figure 11 in chapter 3. The simple idea was to replace the rain gauge measured rainfall in existing adjustment methods with measured rainfall-runoff.

Traditional adjustment based on rain gauges are performed either by estimating the power law parameters of the Z-R relationship or by estimating a bias correction factor for a fixed Z-R relationship. These two approaches have been the basis for the development of the two rainfall-runoff based adjustment methods presented in this Ph.D. thesis. The main challenge of using rainfall-runoff based adjustment methods are to close the rainfall-runoff mass-balance for the given catchment. However, methods exist to handle these challenges (Ahm and Rasmussen, 2015b; Ahm et al., 2016a, 2016c).

The small well-defined urban catchment (BEWARE) described in the previous chapter and by Ahm and Rasmussen (2015a) were used for the development of a Z-Q relationship (Ahm and Rasmussen, 2015b) based on the Z-R relationship (Marshall and Palmer, 1948).

$$Z = a \cdot R^b \rightarrow R = \left(\frac{Z}{a}\right)^{\frac{1}{b}} \quad (2)$$

where Z is the radar reflectivity [ $mm^6/m^3$ ], R is the radar rainfall intensity [ $mm/hr$ ], and  $a$  and  $b$  are the power law parameters. Equation 3 shows the Z-Q relationship.

$$Z = a \cdot RM^{-1}(Q)^b \rightarrow Q = RM \left(\left(\frac{Z}{a}\right)^{\frac{1}{b}}\right) \quad (3)$$

where Z is the radar reflectivity [ $mm^6/m^3$ ], Q rainfall-runoff [ $m^3/s$ ],  $RM^{-1}$  is the inverse function of the transfer function ( $RM$ ) between rainfall and runoff (runoff model), and  $a$  and  $b$  are the power law parameters.

Ahm and Rasmussen (2015b) showed how the power law parameters for equation 3 can be estimated via an optimization process where the error between radar-rainfall-runoff and observed rainfall-runoff are minimised. The study showed that the Z-Q relationship performed equally to the Z-R relationship when applied for estimating radar-rainfall-runoff. The study was performed on a hydrological perfect catchment where both runoff and rain gauge measurements were obtained under ideal conditions. If the Z-R relationship were to be based on rain gauges located outside the catchment area, a lower performance of the Z-R relationship is expected because of representativeness errors of the rain gauges.

Ahm and Rasmussen (2015a, 2015b) showed that the correlation between rain gauge measurements and runoff measurements was close to perfect for the BEWARE catchment. On the data basis used for these studies, it was not possible to statistically distinguish the runoff coefficient from 1 and the initial loss from 0. At the time of writing this thesis more

data was available. Figure 28 shows a scatterplot of corresponding rainfall and rainfall-runoff depths for all rainfall events measured by the *BEWARE* measurement station in 2014.

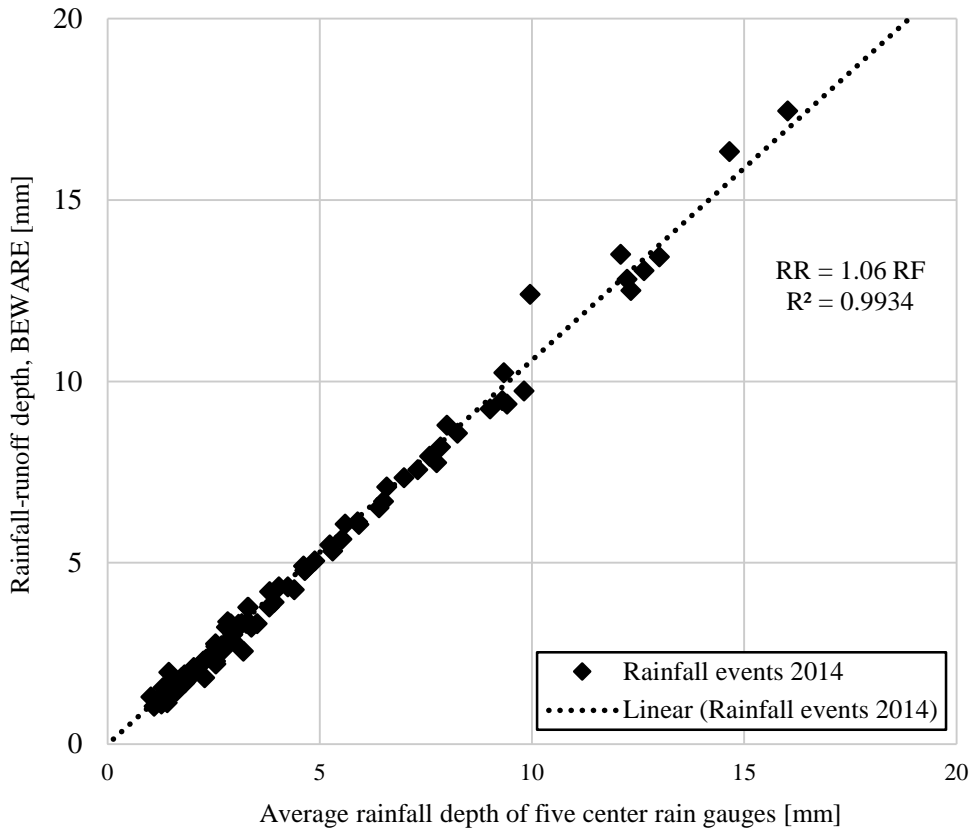


Figure 28: Corresponding measurements of rainfall (RF) depth and rainfall-runoff (RR) depth obtained from the *BEWARE* catchment (Figure 15) in 2014. The initial loss is neglected in the estimation of the runoff coefficient (1.06).

Figure 28 shows that the relation between rain gauge measurements and rainfall-runoff measurements are close to unambiguous. Only a small scattering of the data exist around the mean relation (runoff coefficient). The runoff coefficient is above 1 in average. Thus, the runoff measurement system measures more rainfall than the rain gauge. The average undercatch of 6% corresponds well to experiences from other studies that investigated rain gauge measurement precision (e.g. Hanson et al., 1999; Guo et al., 2001; Duchon and Essenberg, 2001; Ciach, 2003; Sieck et al., 2007).

The Z-Q relationship approach is based on an optimization algorithm. With current computational power it would be impractical to apply this methodology for a larger complex catchment using a fully distributed runoff model as transfer function. However, a large complex catchment just consist of numerous small subcatchments like *BEWARE*. A simplified runoff model may be sufficient for larger complex catchment.

Ahm and Rasmussen (2015b) showed that it is possible to perform radar based weather radar adjustment for small well-defined urban catchments. It also showed that it is necessary to ensure good quality runoff measurements and a closed rainfall-runoff mass-balance.

The runoff based weather radar adjustment principle was also applied for a larger complex combined sewer catchment. Instead of applying the Z-Q relationship approach which would be computational heavy because of the catchment size and complexity, a radar-runoff bias adjustment approach were developed on the basis of the multiplicative radar-rain gauge mean filed bias (MFB) adjustment approach (Smith and Krajewski, 1991).

$$\beta = \frac{\sum_{n=1}^N (G(n))}{\sum_{n=1}^N (RA(n))} \quad (4)$$

where  $\beta$  is the bias adjustment factor [-] between radar and rain gauge rainfall,  $G$  and  $RA$  are the accumulated rain gauge and radar rainfall depths [mm] for each radar-rain gauge pair for a given time period, and  $N$  is the total number of radar-rain gauge pairs. The developed radar-runoff bias adjustment method is formulated as following (Ahm et al., 2016b).

$$\beta = \frac{RO_{obs}}{RA_{AWM} \cdot \varphi \cdot A} \quad (5)$$

where  $\beta$  is the bias adjustment factor [-] between radar-runoff and observed rainfall-runoff.  $RO_{obs}$  is the observed accumulated rainfall-runoff [ $m^3$ ],  $RA_{AWM}$  is the accumulated area weighted mean (AWM) radar rainfall depth [m] for the catchment,  $\varphi$  is the AWM runoff coefficient [-] for the catchment and  $A$  is the area size of the catchment [ $m^2$ ].

The main challenge of using equation 5 for complex combined sewer catchments is to close the rainfall-runoff mass-balance and thereby quantify the rainfall-runoff volume ( $RO$ ). Ahm et al. (2016c) presented a method for estimating the rainfall-runoff part of the catchment runoff for a complex combined sewer catchments based on mass-balance principles. It is therefore necessary to account for all flow sources in the catchment. The catchment runoff is usually monitored at the inlet to WWTP, but for example, CSOs are seldom monitored. Ahm et al. (2016a) presented three software sensor approaches that can be used to quantify CSO discharge flow rates. Both studies were developed, tested and verified under real practical conditions in the Viby catchment described in the previous chapter.

Beside the challenge of quantifying the rainfall-runoff, it is also important to estimate the AWM runoff coefficient accurately for the catchment. The runoff coefficient represents the hydrological losses in the catchment between rainfall and runoff. Ahm et al. (2013) presented a method for estimating the relative distribution of subcatchment runoff coefficients by the use of weather radar data and a single downstream runoff sensor.

The studies performed by Ahm et al. (2013) and Ahm et al. (2016b) were based on 21 and 11 rainfall events, respectively, in the Viby Catchment. The 21 rainfall events were measured in 2011 and the 11 rainfall events were measured in 2014. Figure 29 shows a scatterplot of the corresponding rainfall and rainfall-runoff depths for the two data periods.

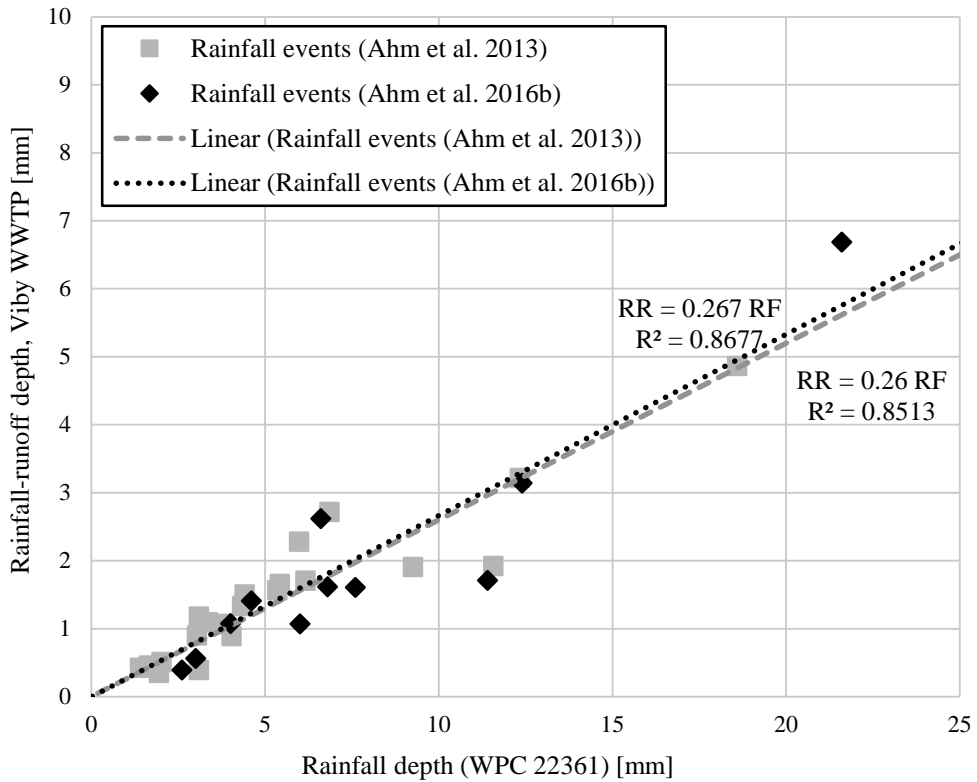


Figure 29: Corresponding measurements of rainfall (RF) depth obtained from WPC 22361 (Figure 26) and rainfall-runoff (RR) depth obtained from runoff measurements at Viby WWTP (Figure 26). The initial loss is neglected in the estimation of the runoff coefficients for the two periods (0.26 and 0.267).

Figure 29 shows that the mean relation (runoff coefficient) and the scattering of the two data periods are similar. The scattering of data in Figure 29 is significantly different from the scattering in Figure 28 (*BEWARE*). As described in the previously chapter, *BEWARE* is a small well-defined urban catchment where there is unambiguity between rainfall and runoff. This is not the case for the larger complex Viby catchment. The increased scattering is due to nonlinearity in rainfall-runoff relation, varying surface runoff characteristics, and representativeness errors of the rain gauge. Going from a small well-defined catchment to a large complex catchment will introduce more uncertainty. Thus, the uncertainty is not inflated unrealistically to use radar-runoff based adjustment methods.

For larger catchments it is difficult to describe the nonlinearity and proportionality accurately since it is practically impossible to describe all rainfall-runoff processes in the catchment in details. Thus, this Ph.D. project have proven that it is possible to use radar-runoff based adjustment methods for larger complex catchment (Ahm et al., 2016b). Because of the increased uncertainty, more events are needed for calibration for the Viby catchment than for the *BEWARE* catchment.

By the use of the methods to close the rainfall-runoff mass-balance presented by Ahm et al. (2016a, 2016c) the radar-runoff based bias adjustment method (eq. 5) were tested in the

Viby catchment. Ahm et al. (2016b) showed that the radar-runoff bias adjustment method performed similar to the radar-rain gauge MFB adjustment method. However, if the rain gauge located within the catchment were excluded for the radar-rain gauge MFB adjustment the performance decreased. If a radar-rain gauge MFB adjustment is applied for weather radar urban drainage applications, it is important to include local rain gauges in the bias adjustment. If no rain gauges exist within or in the near proximity of the catchment, the study indicates, that a more accurate radar-rainfall-runoff estimate is obtained by the use of a radar-runoff bias adjustment instead of a radar-rain gauge MFB bias adjustment. However, the study was performed on a limited number of rainfall events. A definitive and general conclusion requires different types of case study catchments and a larger number of rainfall events.

A short summary and conclusions of each supporting paper for this thesis is given in the following sections. The summaries and conclusions are focused towards the research objectives in this thesis.

## **PAPER I: ESTIMATING SUBCATCHMENT RUNOFF COEFFICIENTS USING WEATHER RADAR AND A DOWNSTREAM RUNOFF SENSOR**

**Reference:** Ahm, M., Thorndahl, S., Rasmussen, M. R., and Bassø, L. (2013) Estimating subcatchment runoff coefficients using weather radar and a downstream runoff sensor. *Water Science and Technology*, 68(6), 1293–9. DOI: <http://dx.doi.org/10.2166/wst.2013.371>.

**Summary:** This paper presents a method for estimating runoff coefficients of urban drainage subcatchments based on a combination of high resolution weather radar data and flow measurements from a downstream runoff sensor. Traditionally, engineers use regression analysis of corresponding measurements of rainfall depth and runoff depth from multiple rainfall events to estimate the runoff coefficient for a given catchment. However, to estimate runoff coefficients at subcatchment level by that methodology it is necessary to install a rain gauge and a flow meter in each subcatchment. By utilising the spatial rainfall variability measured by radar over a catchment, it is possible to estimate runoff coefficients at subcatchment level only using a single downstream runoff sensor for the whole catchment and radar data. The method presented in this paper were demonstrated through a case study of an urban drainage catchment (678 ha) located in the city of Aarhus, Denmark.

**Conclusions:** This study proved that it is possible to estimate runoff coefficients at subcatchment level by the use of radar data and runoff measurements from a single downstream flow sensor. The method utilise the fact that varying rainfall distributions over a catchment will result in different catchment runoff responses. The estimation is based on an optimization of a system of linear equations.

*In relation to the objectives of the present Ph.D. thesis:* This study proved that it is possible to directly couple weather radar and runoff data in time and space even though they are two very different types data. However, the study also indicated, that good data quality are necessary to relate the data directly.

## 5.1. PAPER II: RAINFALL MEASUREMENT BASED ON-SITU STORM DRAINAGE FLOW SENSORS

**Reference:** Ahm, M. and Rasmussen, M. R. (2015) Rainfall measurement based on in-situ storm drainage flow sensors. Urban Water Journal.  
DOI: <http://dx.doi.org/10.1080/1573062X.2015.1057176>.

**Summary:** Data for adjustment of weather radar rainfall estimations are mostly obtained from rain gauge observations. However, the density of rain gauges is often very low. Yet in many urban catchments, runoff sensors are typically available which can measure the rainfall indirectly. By utilising these sensors, it may be possible to improve the ground rainfall estimate, and thereby improve the quantitative precipitation estimation from weather radars for urban drainage applications. To test the hypothesis, this paper presents a rainfall measurement method based on flow rate measurements from well-defined urban surfaces. The principle was used to design a runoff measurement system in a parking structure in Aalborg, Denmark. The upper level of the parking structure is an impermeable concrete surface with an exposed drainage systems beneath. This makes the structure a perfect location for a combined urban rainfall-runoff measurement station. Hence, it is possible to exclude (minimise) uncertainties related to infiltration, inflow from other systems, hydraulic backwater effects etc.

The functionality of the runoff measurement system as a rainfall measurement systems were elevated against rain gauges placed centrally in the catchment area. The evaluation included 69 rainfall events over a period of eight months.

**Conclusions:** This study showed that runoff measurements from well-defined urban surfaces perform just as well as well-placed rain gauges. Two different types of rain gauges were used: disdrometer and tipping bucket rain gauges. Only small variations between the different sensors were observed. On the basis of data from the runoff measurement system and rain gauges, the initial loss and the runoff coefficient of the catchment were estimated to 0 and 1, respectively.

*In relation to the objectives of the present Ph.D. thesis:* This study proved that it is possible to utilise runoff flow sensors to measure the rainfall intensities over an urban catchment. However, this study was performed on a - from a hydrological point of view - perfect catchment with a perfect mass balance. Hence, no infiltration, exfiltration, overflow structures etc. For larger urban catchments it will be necessary to take these effects into account.

Due to the high consistency between runoff measurements and rain gauges, it was also proven, that the measurement station is suitable for further studies of radar-runoff adjustment principles. It is possible to use the measurement station to evaluate radar-runoff adjustment methods under controlled circumstances without concerns about rainfall-runoff mass-balance inaccuracies.



## 5.2. PAPER III: WEATHER RADAR ADJUSTMENT USING RUNOFF FROM URBAN SURFACES

**Reference:** Ahm, M. and Rasmussen, M. R. (2015) Weather radar adjustment using runoff from urban surfaces. *Journal of Hydrologic Engineering*. DOI: [http://dx.doi.org/10.1061/\(ASCE\)HE.1943-5584.0001299](http://dx.doi.org/10.1061/(ASCE)HE.1943-5584.0001299).

**Summary:** Weather radar data used for urban drainage applications are traditionally adjusted to point ground references (e.g. rain gauges). However, the available rain gauge density for the adjustment is often low, which may lead to significant representativeness errors. Yet, in many urban catchments, rainfall is often measured indirectly via runoff sensors. This paper presents a method for weather radar adjustment based on runoff observations (Z-Q adjustment) as an alternative to traditional Z-R adjustment based on rain gauges. Data from a monitoring station in Aalborg, Denmark, was used to evaluate the flow based weather radar adjustment method against traditional rain gauge adjustment.

The evaluation of the radar-runoff adjustment method was based on nine rainfall events and performed by comparing radar-modelled runoff to observed runoff. Three different evaluation statistics from the field of watershed modelling were used (NSE, RSR and PBIAS) to evaluate the performance of the methodology. The methodology was both tested on event basis and multiple events combined.

**Conclusions:** This study showed that the presented Z-Q adjustment performed similar to a traditional Z-R adjustment. This opens up to the possibility of using flow measurements as an alternative to or in combination with rain gauges as adjustment basis for weather radar data. The estimated Z-Q and Z-R relationships are found to be within the ranges of Z-R relationships found in the literature.

*In relation to the objectives of the present Ph.D. thesis:* This study proved that it is possible to utilise flow measurements of rainfall-runoff as ground observation for weather radar adjustment. However, this study was performed on a - from a hydrological point of view - perfect catchment with a perfect mass balance. Hence, no infiltration, exfiltration, overflow structures etc. For larger urban catchments, it will be necessary to consider these effects.

The Z-Q adjustment method was compared to a Z-R adjustment based on ideally placed rain gauges. In practice, rain gauges are rarely placed ideally for weather radar adjustment. Hence, this may affect the performance a Z-R adjustment negatively in practice for larger catchments.

The Z-Q adjustment method has the potential to improve weather radar adjustment for urban areas, but the study also showed, that it requires high quality flow measurements and detailed catchment descriptions.

### 5.3. PAPER IV: ESTIMATION OF COMBINED SEWER OVERFLOW DISCHARGE: A SOFTWARE SENSOR APPROACH

**Reference:** Ahm, M., Thorndahl, S., Nielsen J.E. and Rasmussen, M. R (2016) Estimation of combined sewer overflow discharge: A software sensor approach. Manuscript submitted to Urban Water Journal.

**Summary:** Combined sewer overflow (CSO) structures are constructed to effectively discharge excess water during heavy rainfall to protect the urban drainage system for hydraulic overload. Consequently, most CSO structures are not constructed according to basic hydraulic principles for ideal measurement weirs. It can therefore be a challenge to quantify the discharge volumes from CSOs. Quantification of CSO discharge volumes are important in relation to the increased environmental awareness of the receiving water bodies in Europe. Furthermore, CSO discharge quantification is essential for closing the rainfall-runoff mass-balance in combined sewer catchments. A closed mass-balance is essential for stormwater runoff based weather radar adjustment methods and calibration of all urban drainage models based on mass-balance principles. An unclosed mass-balance can result in significant uncertainties and ambiguities in the rainfall-runoff relations for a given catchment.

This study presents three different software sensor concepts, which can be used to estimate CSO discharge volumes from hydraulic complex CSO structures by the use of simple water level measurements. The three software concepts have been tested and verified under practical conditions. All three concepts have proven to be accurate when compared to electromagnetic flow measurements of the CSO discharge.

**Conclusions:** The study showed that it is possible to use simple, but accurate, water level sensor for software sensors to estimate CSO discharge volumes accurately. Two of the software sensors were based on data-driven Q-h relation, which needed to be calibrated to discharge observations. The third software sensor were based on computational fluid dynamic (CFD) simulation of the physical CSO structure. Hence, the third sensor is independent of any calibration. With the use of CFD simulations it is possible to derive a Q-h relation for a location in CSO structure. However, the study also showed, that the software sensors are sensitive to inaccuracies in the estimated water levels. Hence, it is necessary to use precise water level sensors to obtained accurate CSO discharge estimates.

*In relation to the objective of the present Ph.D. thesis:* This study proved that it is possible to quantify the CSO discharge load for hydraulic complex CSO structures with multiple weir levels and grating. Hence, it is possible to close the rainfall-runoff mass-balance for a combined sewer catchment in relation to CSOs. A closed mass-balance is necessary for radar-runoff adjustment.

## 5.4. PAPER V: URBAN RUNOFF MEASUREMENTS: A CASE STUDY OF SEPARATING RAINFALL FLOWS IN A COMPLEX COMBINED SEWER CATCHMENT

**Reference:** Ahm, M., Thorndahl, S., and Rasmussen, M. R. (2016) Urban rainfall-runoff measurements: A case study of separating rainfall flows in a complex combined sewer catchment.  
Manuscript prepared for Water Science and Technology.

**Summary:** Quantification of rainfall-runoff is an advantage for effective management of drainage systems and wastewater treatment plants (WWTP). Knowledge about how the urban drainage system responds to rainfall under practical conditions can improve the operation of both drainage system and WWTP. Accurate measurement of the rainfall-runoff makes it possible to close the rainfall-runoff mass-balance for the given catchment. A closed mass-balance is essential for calibration of all urban drainage models and integrated real time control systems for urban drainage systems based on mass-balance principles. Furthermore, a closed rainfall-runoff mass-balance is a necessity for weather radar adjustment methods based on stormwater runoff measurements from an urban drainage catchment.

It is a challenge to separate the rainfall component from the catchment runoff hydrograph combined sewer catchments. This paper presents a simple method based on mass-balance principles to separate the rainfall component for a complex combined sewer catchment with a CSO, basin and pump lines from other catchments. The presented method compensates for these flows to estimate the actual rainfall-runoff hydrograph. The method have proven to be precise for the tested case study catchment.

**Conclusions:** This study showed that it is possible to estimate the rainfall-runoff hydrographs from a complex combined sewer catchment using a simple mass-balance principle. However, the method requires that it is possible to account for all flow terms in the catchment mass-balance. Inlet flows to WWTPs and pump lines are often monitored by flow meters whereas combined sewer overflows and basins usually are unmonitored. If these structures exist in the catchment, it is necessary to account for these. However, as demonstrated in this study methods exist to handle these challenges. Based on the tested catchment the method have proven to be accurate for estimating rainfall-runoff volumes. When compared to rain gauge observations the volumetric error for all evaluation events is 2.1%.

*In relation to the objective of the present Ph.D. thesis:* This study proved that it is possible to quantify rainfall-runoff volumes in a complex combined sewer catchment under practical conditions. Hence, it is possible to close the rainfall-runoff mass-balance for a complex combined sewer catchment with CSOs, basins and pumps. Consequently, it should be possible to use stormwater runoff measurements for weather radar adjustment.

## 5.5. PAPER VI: WEATHER RADAR BIAS ADJUSTMENT UTILISING IN-SITU STORM DRAINAGE SENSORS

**Reference:** Ahm, M., Thorndahl, S., Nielsen J.E. and Rasmussen, M. R (2016) Weather radar bias adjustment using in-situ storm drainage sensors. Manuscript prepared for Journal of Hydrology.

**Summary:** Weather radar measurements is traditionally adjusted to rain gauge observations before applied in hydrological applications. Different radar-rain gauge adjustment methods exist, but the mean field bias adjustment approach is commonly used within hydrology. However, for urban drainage applications, the rain gauge density is often low, which may result in significant representativeness errors. These representativeness errors may lead to significant errors in radar based rainfall-runoff predictions.

This paper present a bias adjustment method based on rainfall-runoff measurements. By the use of a radar-runoff based bias adjustment method a more representative bias adjustment for urban drainage may be obtained compared to radar-rain gauge based bias adjustment. Especially, if the radar-rain gauge bias adjustment cannot be based on rain gauges located in or near to the given catchment. The radar-runoff based bias adjustment method were evaluated in a complex combined sewer catchment in Aarhus, Denmark, by comparing the presented method to the commonly used radar-rain gauge mean field bias adjustment approach. The evaluation was performed by comparing radar based rainfall-runoff volumes to observed rainfall-runoff volumes. The results show that the radar-runoff bias adjustment perform similar to the radar-rain gauge field bias adjustment approach.

**Conclusions:** This study showed that it is possible used rainfall-runoff observation from a complex combined sewer catchment to bias adjust weather radar data for hydrological applications. The presented method performed similar to a traditional radar-rain gauge mean field bias adjustment approach based on three rain gauges.

*In relation to the objective of the present Ph.D. thesis:* This study proved that it is possible to used rainfall-runoff observations from urban drainage systems to adjust weather radar data for hydrological applications. The main challenge of using a rainfall-runoff based bias adjustment is quantification of the rainfall-runoff. Methods exist to handle these challenges.

The performance of the radar-runoff and radar-rain gauge adjustment were similar. However, if the most representative rain gauge were excluded from the radar-rain gauge bias adjustment the performance decreased. As expected, a radar-runoff based bias adjustment is more representative for the catchment than a radar-rain gauge based bias adjustment based on rain gauge outside the catchment.

## CHAPTER 6. CONCLUSION

The main objective of this Ph.D. thesis was to investigate the potential of using runoff measurements from in-situ stormwater drainage sensors to adjust and improve weather radar QPE for urban drainage applications.

This Ph.D. study has proved that it is possible to adjust weather radar measurements to rainfall-runoff measurements from urban drainage catchments. Two significantly different urban drainage catchments, in size and complexity, were used to test the adjustment methods developed in this study under practical conditions. The evaluation of the methods were performed by comparing the radar predicted rainfall-runoff to measured rainfall-runoff. The radar-runoff adjustment methods were compared to similar radar-rain gauge adjustment methods.

The evaluation of the radar-runoff adjustment showed similar performance as to radar-rain gauge adjustment. The radar-rain gauge adjustment included rain gauges located within the catchment. If rain gauges located within the catchment were excluded from the radar-rain gauge adjustment, the performance decreased compared to the radar-runoff adjustment. It can be concluded that the methods perform similar when the radar-rain gauge adjustment is based on rain gauges representative for the catchment. The radar-runoff adjustment methods perform better if no rain gauges within or in the near proximity of the catchment are available for the adjustment.

The main challenge of using radar-runoff based adjustment is to close the rainfall-runoff mass-balance and quantify the rainfall-runoff. If combined sewer overflows, basins, pumps, etc. exist in the catchment, it is necessary to account for the combination of these flows in order to quantify the resulting rainfall-runoff hydrograph. It is challenging to close the rainfall-runoff mass-balance for complex combined sewer catchments. A great effort of this Ph.D. study was dedicated to closing the rainfall-runoff mass-balances for two case study catchments. It requires that all flow sources either are monitored or can be quantified in other ways. Consequently, a radar-runoff adjustment can seem impractical compared to radar-rain gauge adjustment. On the other hand, it can be difficult to find suitable measurement locations for rain gauges in build-up urban areas.

### 6.1. PERSPECTIVES FOR THIS STUDY

To obtain good and reliable results from advanced analyses and RTC of distributed urban drainage systems, high-quality measurements of flow and water levels in critical points in the system are required for calibration of the runoff models. Furthermore, RTC requires online measurements of current states in the drainage system to predict future states and adjust the control strategy. Hence, high-quality measurements of flow and water levels will probably be more common in the future since they are required for these purposes. If high-quality rainfall-runoff measurements are available, implementation of a radar-runoff based adjustment is straightforward.

Radar-runoff and radar-rain gauge adjustment are not viewed as two mutually exclusive weather radar adjustment methods. It might be beneficial to combine the two methods to

obtain a larger data basis for the adjustment. Furthermore, it might be beneficial to use the methods for different types and purposes of urban drainage weather radar applications.

If a larger amount of capital were available for improving prediction of flow and water levels for a fictive city in Denmark that potentially could benefit from RTC, I would recommend the following:

The existing C-band weather radar network operated by DMI in Denmark would be sufficient for rainfall nowcasts of 0-2 hours lead-time. If combined with numerical weather models, the rainfall nowcast could be extended up to 6 hours or more (Jensen, 2015). Limitations still exist in relation to growth and decay of the rainfall and discrepancies between radar-rainfall and the “true” ground rainfall needed for urban drainage applications.

To obtain the desired spatiotemporal rainfall resolution of urban drainage applications and to minimize discrepancies between radar-rainfall and the “true” ground rainfall, X-band weather radars could be placed near to the city. Hence, weather measurements are obtained low in the atmosphere above the city. By combining the C-band and X-band weather radar products, a combined product with high spatiotemporal resolution above the city and a long nowcast lead-time could be obtained (Nielsen, 2013).

The weather radar adjustment would take place in three stages: (1) Rain gauges located far away from the city would be used to adjust the weather radar rainfall moving towards the city. (2) When the rainfall reaches the city, rain gauges located within the city are weighted higher in the adjustment. (3) When rainfall-runoff is observed in the urban drainage system, runoff measurements are weighted highest in order to ensure a good rainfall-runoff mass-balance. High quality rainfall-runoff measurements from the urban drainage system would be available since it is essential for RTC to have accurate measurements of current states in the system.

## **6.2. SUGGESTIONS FOR FUTURE WORK**

A relevant subject for this thesis, which has only been worked on briefly, is the representativeness errors of rain gauge rainfall data in relation to urban drainage applications in general and weather radar adjustment. As described in this thesis, studies have been performed within this subject. However, it would be logical to utilise the measurement station, *BEWARE*, to study the correlation between the radar-rain gauge adjustment performance and the distance between rain gauge and catchment. All uncertainties related to the runoff process have been minimized to the possible extent in the *BEWARE* catchment. The study would most likely give a qualitative estimate of when it is beneficial to use radar-runoff adjustment instead of radar-rain gauges adjustment.

The radar-runoff adjustment developed and tested on the larger complex catchment were based on the mean field bias approach using accumulated rainfall and runoff volumes. It may be beneficial to adopt the Z-Q adjustment method for larger complex catchment. Then corresponding rainfall and runoff time series could be used to adjust the power law parameters during the rainfall. A real-time adjustment could potentially compensate for all discrepancies between radar and runoff and thereby improve prediction of flow and water levels.

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DOI: [http://dx.doi.org/10.1016/S1464-1909\(99\)00103-3](http://dx.doi.org/10.1016/S1464-1909(99)00103-3).