Application of rainfall data from radar versus rain gauge in urban water management

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MSc Thesis
Water Engineering & Management
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University of Twente, the Netherlands

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SUMMARY

Rainfall information provides important input for several analyses in rainfall-runoff models and consequent decision-making. Current models use spatially uniform information of rain gauges as input for the model simulations. However, in the past decades also rainfall information of weather radar has become available. In addition to rain gauge point measurements, radar data also provide information of the spatial distribution in rainfall events. This information could be significant for use in urban water management regarding analysis of the drainage system and the execution of the urban water tasks. Especially the increased spatial and temporal resolutions of the radar in the last years have enhanced the potential for radar data application at small spatial scales of urban surroundings. These developments provided the opportunity for this research to examine the effect of spatially variable rainfall data from radar on the rainwater volumes and model simulations of water at street in comparison with spatially uniform rainfall data from rain gauges. The study has been conducted by means of a PC-raster rainfall-runoff model for a case study in Amersfoort. In addition, implications of radar data use on urban water management issues have been discussed.

First, appropriate heavy rainfall events in the radar data series have been identified to serve as model input for the study area. For this reason, a selection was made on the basis of extremeness and spatial variability in the events. In total, twelve events have been selected from which seven in the period 1998-2008 and five in the period 2009-2010. Rainfall data from the corresponding events of the rain gauge information have been analysed. Here, already vast differences appeared between the rainwater volumes of the two rainfall information sources in the selected rainfall events. In the period 1998-2008, with rain gauge measurements outside the model area, these differences are 70% on average. Since 2009, a municipal rain gauge in the centre of the model area has been employed for which the rainfall depths are more equivalent to the radar input (difference of 22% on average).

A rainfall-runoff model has been applied to simulate surface runoff and water at street occurrence during the selected rainfall events. Development of the model has been a part of the study, including calibration, validation and several model improvements. The latter mainly consisted of adjustments for a suitable representation of the sewage system for which specific information of area experts was implemented. Only limited information of historical water inconveniences was available, which hampered optimal calibration and validation.

After the processing of the model, the selected rainfall events have been simulated. The outcomes of the model runs from spatially variable radar, spatially averaged radar and rain gauge data have been compared. The comparison of the two radar data sources with equal rainwater volumes aimed at an assessment of the effect of spatial variability. The comparison between the radar and rain gauge data was supposed to reveal the effects of the different observation techniques and the effects of point measurements compared to spatially variable measurements. In general, it turned out that the rainfall input differences resulted in even larger in water at street volumes. The analysis with respect to spatially variable and spatially averaged radar showed the importance of locally heavy rainfall, which could be represented by the spatially variable radar data. Especially these locally high rainfall

depths appeared to contribute significantly to the occurrence of water at street and explain the average difference of 24% between the radar data sources. The comparison between radar and rain gauge data showed large differences, ranging from 36% up to a situation in which 68 times more water at street have been simulated by input from the rain gauge. In spite of the sometimes comparable rainfall depths, deviating input with respect to rainfall intensity and duration have demonstrated its value for the model calculations. Besides, the measurement location of the rain gauge seriously affected the model output. In some cases, the rain gauge information from outside the model area has not even generated water at street, although water inconveniences have been simulated with radar input and have also been reported by the municipality.

The implication of spatially variable rainfall information on the urban water management tasks is the improved possibility to analyse local bottlenecks. Many spatial characteristics of the rainfall events are integrated in the radar data and provide locally specified input, which could explain experienced water inconvenience. In addition, spatially distributed data give opportunities to test the response of the drainage system for various rainfall patterns. This way, decision-making regarding the necessity of measures is supported. Since the urban water tasks require a problem-orientated approach, spatially variable radar data provide a suitable tool for more appropriate and effective solutions. Such measures could for instance be implemented locally to improve the infiltration capacity, which appeared to be the most influential parameter according to the sensitivity analysis. Besides, measures that increase local water storage are recommendable as they decrease the discharge and runoff volumes. Current policies also encourage the mentioned measure types where they enable improvements to the quality of the urban surroundings. Examples of effective measures are green roofs, rainwater butts and permeable pavements. Moreover, the increase of radar data series in the coming years will give insight in the need to integrate local rainfall distributions in the normative rainfall events of urban water management.

The reliability of the model results is a point of attention due to the lack of information regarding historical water inconveniences and the limited understanding of detailed rainfall-runoff processes inside the urban area. This mainly includes infiltration processes on paved or semi-paved surfaces and the drainage processes by the sewage system. Moreover, the early phase in the model development has resulted in some limitations regarding the allocation of surface runoff. Nevertheless, the model outcomes and its corresponding conclusions are supposed to be sufficiently reliable in view of the research objective since accurate assessment of inundation areas and inundation depths are beyond the scope of this study.

PREFACE

The research presented in this report has been conducted on behalf of the two years master's Water Engineering & Management. Moreover, this thesis is the conclusion of my five year study Civil Engineering at the University of Twente in the Netherlands. During the execution of the research, I worked externally for half a year at research and consulting agency HydroLogic in Amersfoort.

The occasion for the subject in this MSc thesis is as follows. Since some courses paid attention to the serious problems of water drainage in the urban area, my interest has been taken for this discipline in the water management field. The specific characteristics of the urban area fascinated me as they require a specific approach in comparison to the rural areas. Besides, the interface between water management issues and the extreme rainfall analysis appealed to me. This is explained by the potential of weather radar, which has drawn my attention as a result of its opportunities for the representation of local rainfall variations. Moreover, I also considered a course in the direction of meteorology before my choice for the study Water Engineering and Management. Therefore, my interests for urban water management and climatology have been joined in a research on extreme rainfall simulations in the urban area.

With help of HydroLogic, the first lines of the possible research have become clear. During the preparation of the thesis project they provided the opportunity to perform the study in the context of the project HydroValley in which the actual study area in Amersfoort was participating. Next to this, the software at HydroLogic and the corresponding entrance to the radar rainfall data have been essential for the method and analysis in this study.

First of all, I would like to thank the members of the thesis committee for their support and supervision during the graduation period. In particular, I would like to thank Denie Augustijn and Martijn Booij for their directional research comments and extensive feedback during the realization of this report. I would like to thank Marlies Zantvoort for her instructions and elaborate feedback as my main guide at HydroLogic. Also I owe thanks to Maarten Spijker for developing the basis structure of the model in which the model calculations of this study have been performed. Furthermore, I am grateful for the areal and historical information provided by the area experts of the city of Amersfoort. In case I forgot to mention someone who contributed to the fulfillment of the research; also many thanks of course!

Sander Siebelink
Brummen, March 2011

CONTENTS

1 INTRODUCTION

1.1 Motivation

Water inconveniences due to extreme rainfall events may disrupt everyday life and may even cause serious damages or casualties. Especially the urban area is vulnerable to high rainfall depths in relatively short periods of time, due to the quick runoff of storm water (Buishand & Wijngaard, 2007). Sewage systems are sometimes not able to cope with the large rainwater amounts and water at street situations arise consequently. Since the occurrence and extremeness of such rainfall events could not be well predicted beforehand, the surroundings have to be designed according to the accepted risks. For the design and analysis of the sewage systems, normative rainfall depths are applied that are based on the long time series of rain gauge stations (see Figure 1-1). However, alternative rainfall estimations by weather radar appeared on the scene since the late nineties. This research focuses on the application of radar data for urban water management issues, including the differences with respect to the use of rain gauge information.

1.1.1 Techniques, development and application of weather radar

Since the weather radar was put into operation in 1998 in the Netherlands, its observations have become more and more available besides the data of ground rain gauges. This radar information is gathered from measurements of radar stations in De Bilt (see Figure 1-1) and Den Helder, which provide rainfall data for the whole country.

Figure 1-1: Left: Weather radar of the KNMI in De Bilt (picture by Iwan Holleman, KNMI). Right: Automatic rain gauge of the KNMI (KNMI, 2009).

Weather radar transmits radio-frequency waves into the atmosphere and receives the reflected signals from hydrometeors like rain, hail or snow as echo powers, from which reflectivity factors can be calculated. From the direction of the antenna and the time between the emission and the reception of the echoes, the location of the precipitation can be derived. The conversion from radar reflectivity data towards radar rainfall maps includes the application of a relation between the reflectivity and the rainfall intensity. Furthermore, the information has to be converted to a rectangular grid which results in a spatial resolution of 1 km for the current operational weather radars in the Netherlands (Holleman & Beekhuis, 2010). The Dutch meteorological institute (KNMI) distributes accumulated radar images with temporal scales of 5 minutes, 3 hours and 24 hours (KNMI, 2009).

The radar products are used for several functions such as aviation, navigation, agriculture and water management. An example of application is a warning system which is in use by over 50% of the Dutch water boards since 2003 (Overeem, 2009). Another possible application of weather radar is the prediction of flooding or other extreme events. However, the use of weather radar forecasts is still difficult due to the divergent behaviour of rainfall events (Werner & Cranston, 2009). Extreme storms are mentioned in particular as they can abate in short time, change direction or even suddenly arise. Moreover, water managers have become more interested in applying weather radar data for urban water management since several technical developments have enabled higher resolution radar data in the last years. Municipalities see opportunities to use this high resolution rainfall information for analysis of their urban drainage system and for real time applications (Einfalt et al., 2004). These developments have also received more attention in projects of research and consulting agencies. In this way, the opportunity has been created to examine the use of radar rainfall information in urban water management for this thesis study. Its use for the identification and analysis of water at street situations may provide added value in comparison to rain gauge data.

1.1.2 Importance of more detailed quantitative precipitation estimates

The rainfall amounts and intensities are an important source of information for a sound design of sewage systems or for testing of regional water systems including water works. In the present situation, modelling of water flows and water levels by the water managers is based on rainfall information from rain gauges which is taken uniformly or interpolated between some measuring stations. However, radar image examples show that the information obtained from one gauge not always enables a good representation of the actual rainfall amounts in the whole area (see Figure 1-2). This can be attributed to the limited density of the rainfall observations by the gauges (Delrieu, 2009). In Figure 1-2, the black dot represents the rain gauge in Amstelveen that recorded 30 mm while the radar, calibrated by the rain gauge, recorded amounts below 20 mm in the southeast and above 40 mm in the northwest only over a few kilometres distance.

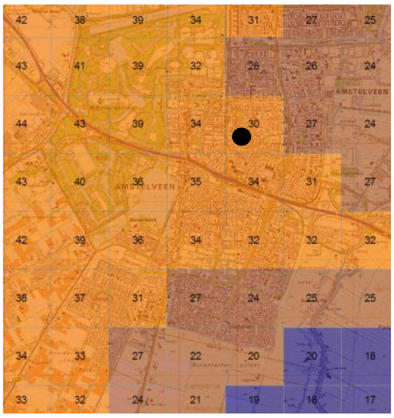


Figure 1-2: Rainfall amounts of 25/26th of May 2009 in the surroundings of Amstelveen according to the weather radar. The black dot represents the rain gauge location (30 mm).

Based on the information from the rain gauge, rainfall-runoff models are being calibrated and validated with the rainfall uniformly distributed over the area. Subsequently the models are used to analyse and decide whether measures and investments are required to solve the bottlenecks in the water system. It is questionable whether all the attempts to optimize the hydrological models are valuable if the rainfall input not realistically represents extreme storms in the area. Therefore, it has added value to investigate the possibility and consequences of applying spatially variable radar data in those models.

1.1.3 Application of weather radar data in previous studies

In literature several research experiences with respect to the use of weather radar data have been described for areas outside the Netherlands.

A study of Jessen et al. (2004) in the North Rhine area, showed good applicability of weather radar for the representation of heavy rainfall events. Five heavy rainfall events have been evaluated by a comparison of adjusted radar data and spatially interpolated rain gauge data. In spite of the difficult verification of the observed spatial variability in the radar images, the comparison has confirmedly shown that the rain gauge data were not able to reflect the maximum rainfall amounts in the area well. In addition, several of the locally heavy rainfall observations by the weather radar were supported by severe damages such as land slides and flooding.

In a study of Einfalt et al. (2004) in several municipalities in Denmark, the application of radar rainfall data was successfully due to detailed representations of local variability in rainfall. The researchers studied several extreme events to determine maximum rainfall events resulting in flooding of small urban catchments. Based on radar data adjusted with rain gauges, detailed rainfall-runoff simulations of extremely spatially distributed rainfall events were obtained.

According to Krajewski & Smith (2002), radar rainfall estimates are promising for engineering, design and management applications in small basins. These uses are characterized by a strong dependency on rainfall rates that can be provided in more detail by radar data than by rain gauges. However, important processes during extreme event runoff in densely urbanized areas are still poorly understood which hamper the controlling abilities (Villarini et al., 2010). To advance the understanding of these processes, accurate rainfall observations for extreme events in small urban areas are needed. The developments in weather radar techniques in the last decade offer opportunities to combat the shortcomings of methods using only rain gauge measurements.

1.1.4 Legal and policy framework

Besides the increased recognition of possible benefits of weather radar application, also motivation for this research is provided by current approaches in governmental legislations.

From the policy “water management in the 21st century” (WB21), the legal standard for flooding in the urban area from surface waters is once every hundred years. However, the accepted frequency of occurrence regarding inconveniences as a result of heavy rainfall is much higher. The sewage system is generally designed to cope with rainfall events with a return period of two years, which implies the occurrence of water excess situations every few years on average. These heavy rainfall events will cause inconveniences like water at street, more serious inconveniences like blockage of arterial roads or damage to buildings. Furthermore, the quality of surface water is threatened by sewage overflows. In the prescription of WB21, some gradations have been made for the water task in the urban area:

- In principal, nuisance because of rainfall events has to be accepted. An example is the occurrence of water at street for short durations.
- More serious inconveniences have to be prevented. This category includes inconveniences which disrupt everyday life or for example economic activities.
- Damage as a result of extreme rainfall events has to be prevented. For example buildings and properties should not suffer damage in case of accumulating water flows or bottlenecks in the urban drainage system.

The task for municipalities in the urban sewage task (VROM, 2008) is to act on problems more than on the norms. Therefore, they have to map locations where the problems occurred in the past. Municipalities should also investigate how the drainage system responds to different rainfall events with corresponding consequences in the urban surroundings. Especially the situation at the surface is considered to be important for a reduction of bottlenecks in the urban area. On the other hand, structural measures to the sewage system are less attractive as they require many financial resources and cause nuisance for the citizens. Moreover, the latter measure category does not offer optimal circumstances to enhance both the water drainage and the quality of the urban surroundings.

1.2 Problem description

Based on the regulations in WB21 and the urban water tasks, current urban water management has to focus on observed problems in the urban drainage system. Analysis of bottlenecks or effects of interventions could be provided by rainfall-runoff simulations of historical heavy rainfall events. This is supposed to be a very useful tool to support decision making for measures and its corresponding investments. However, a good understanding of the rainfall-runoff processes in the urban area requires the use of realistic rainfall information for analysis. This could be hampered by the generally used rainfall data of rain gauges since their measurements are observed at one point in space. Hereafter, the rain gauge data is applied for assessment with spatially uniform rainfall values for a much wider area. Alternatively, they may be treated with interpolation techniques to artificially add spatial variation. By ignoring considerable local rainfall variations, measures could be implemented unnecessarily or measures could not show the expected effect. On the other side, it is possible that required adjustments will not be carried out which may imply risky situations. In the latter case, the risk perception deviates from the real risk of water inconveniences. In contrast, weather radar makes it possible to represent the rainfall input information with high spatial and temporal resolutions as shown in previous studies.

Despite the satisfying representation of local rainfall variations by the radar data for the mentioned studies in section 1.1.3, the effects on model results of rainfall-runoff simulations have not been discussed. These effects have to be examined before sound implementation in practice of urban water management could be considered. The assessment should reveal the propagation of spatial variability and other rainfall characteristics through the model compared to the commonly used rain gauge information. It is the question whether the representation of water inconveniences is more obvious with the use of radar instead of the rain gauge input. In addition, the research is required to find out whether problems occur in conjunction with specific spatial distributions of rainfall events. With the help of the acquired knowledge during this research, application of weather radar products for urban water management could appear beneficial. This experience provides the basis for efficient and tailor-made solutions for urban water task issues. However, first of all the study results are supposed to contribute to the understanding of heavy rainfall characteristics with their effects on surface runoff and water inconveniences.

1.3 Research conditions

1.3.1 Case study

The assessment of extreme rainfall events is performed for a case study that could be handled within the time span of this thesis study. The urban case study gives the opportunity to analyse the application of weather radar data for its particular small spatial scales. A current project in which the Dutch city of Amersfoort and HydroLogic are participating has mainly defined the choice for the case study. For this reason, the urban area of Amersfoort has become subject of a research in which the rainfall analysis and model executions can be carried out.

1.3.2 Limitations of research

In comparison to the generally long time series of the rain gauge stations, weather radar only provides information for almost thirteen years in this study. In addition, the temporal and spatial resolutions are restricted for the radar data from 1998 to 2008 inclusive. However, the observations of the rain gauge stations face similar restrictions with respect to the available temporal resolutions. Moreover, until 2009 measurements of the rain gauges are not available inside the study area. The mentioned aspects affect the study results and are considered in a discussion. Besides, the limitations are also taken into account for the final conclusions.

Secondly, the reliability of the used rainfall-runoff model is questionable. This is mainly caused by the early phase in the development of the model in which this thesis has been conducted. Also the lack of detailed information with respect to observations of surface runoff and water inconveniences are limiting aspects. Nevertheless, some conclusions are drawn since the accurate model results are less interesting for this research. More attention is given to relative differences between the model results for which sufficient reliability of the model is assumed. The limitations of the model provide input for the discussion part of the report.

1.4 Objective

The objective of this thesis is described as follows:

> *Examine the effects of weather radar application in comparison to the use of rain gauge measurements on the total rainwater volume, simulated water excess and possible implications for urban water management*

by

> *selecting and analysing extreme rainfall events in order to simulate water at street situations in an urban case study with a rainfall-runoff model for a comparison of spatially distributed and spatially uniform rainfall data and considering the results in view of the urban water tasks.*

The objective should be achieved by following the outlines of the research model, which is represented in appendix A. Next some research questions are defined in order to fulfil the objective.

1.5 Research questions

The questions in this paragraph provide the guidelines to pass through the stages of the graduation project. The several questions will be discussed in the elaboration of this thesis report and will explicitly return in the study conclusions.

The main aspect of this study is the comparison of radar and rain gauge data in rainfall-runoff simulations. However, for the comparison of the model results between the two rainfall data suppliers, also the difference in the rainfall input is essential knowledge. For this purpose, the following research question has been defined:

1. To what extent does the total rainwater volume in the study area for the identified events of the weather radar data and rain gauge data correspond to each other?

In contrast with the probable variations in rainwater volume between weather radar and rain gauge information, the rainfall data of spatially variable and spatially averaged radar have equal rainwater volumes by definition. Therefore, a comparison between the two different radar runs is most appropriate if only spatial variability is concerned. This results in the next research question:

2. Is the spatial distribution in the identified events meaningful for the simulation of water at street in comparison to a spatially averaged rainfall depth for the whole study area?

Subsequently, also the differences between radar and rain gauge results are examined. Besides the differences concerning spatial distribution of the input data, the following question may also reveal the effects of the measurement location of the rain gauge:

3. What are the effects of the use of radar rainfall information with its higher spatial resolution on the simulated water accumulations in the study area in comparison to the results based on rain gauges?

The differences that have been obtained in the above-mentioned research question may be ascribed to other factors than the resolution or properties of the data itself. Therefore the research question below is intended to assess specific circumstances of the model simulations which could affect the outcomes:

4. What is the dependency of the model results on the specific properties of extreme rainfall events and influencing areal characteristics?

In the questions below, some issues for discussion are introduced. Due to the limitations of both the rainfall data and the rainfall-runoff model, the reliability of the study results has to be discussed. The question should contribute to the awareness of possible uncertainties and their consequences for the model results:

5. What is the meaning of the model output differences between weather radar and rain gauge considering reliability of both the model and the data?

The model outcomes may show some clear bottlenecks in the drainage of storm water. Although it is not a primary goal of this study, short attention is given to possible measures that can be well integrated in the urban environment. Some experiences with the rainfall-runoff model could be directive for the proposed types of measures. Therefore, the next research question has been defined:

6. Which possible measures can be described that correspond to identified influential model parameters?

As prescribed in the urban water tasks, municipalities have to focus on local problems in their urban water management. Furthermore they have to analyse the storm water drainage for various rainfall events. The following question will provide some insight in the possible value that weather radar application may contribute to the achievement of the urban water tasks:

7. What are the implications of weather radar application on the urban water tasks and does the use of radar data hold added value for urban water management in general?

1.6 Approach

1.6.1 Global method

For the analysis of model simulations with radar or rain gauge data, rainfall input of historical events is required. Therefore, the weather radar data will be analysed to abstract some extreme events in the time span of radar data availability. The consequence is that the amount of extreme rainfall events in the radar data will be limited and that events with large return periods are most probably not available. For this reason, the available rainfall events will be selected on the basis of appropriate extremeness criteria to analyse the urban drainage response. It is assumed that in total about ten suitable rainfall events will be available.

The gathered rainfall information will be used for implementation in a PC-Raster rainfall-runoff model, which will simulate the surface runoff and water excess in the study area. Before this, the weather radar data have to be processed for implementation in the model. The general behaviour of the model is assessed with a sensitivity analysis. Furthermore, the model is calibrated and validated as far as this is possible by the available information. Knowledge of water inconveniences during historical events by area experts will be directive for the definition of appropriate parameter values.

As soon as suitable model settings are obtained, the selected rainfall events will be run for spatially variable radar input, spatially uniform radar input as well as spatially uniform rain gauge input. The model results of the case study Amersfoort can be used in two different ways. First, it can clarify the effect of spatially distributed weather radar data in urban water management and secondly it is the point of departure to draw up efficient measures for improvements in the system. The emphasis in this thesis report is set on the first mentioned objective. For this purpose, a quantitative analysis of the model results will be executed to determine the volumes and surfaces of water at street. Based on this information and the type of rainfall input source, the conclusions with respect to the effects of spatial variability can be drawn. Besides, the inundation maps can be used to carry out a qualitative analysis to consider the general picture of the model results with their differences and similarities. A discussion at the end of this report covers some aspects of the second purpose; the consequences for the urban water tasks and improvements in the urban drainage system. However, the extensive identification and assessment of suitable measures should be subject of succeeding studies.

For an overview, the research method is represented in the schematisation of Figure 1-3 below. Also the relation of the particular stages to the research questions has been included.

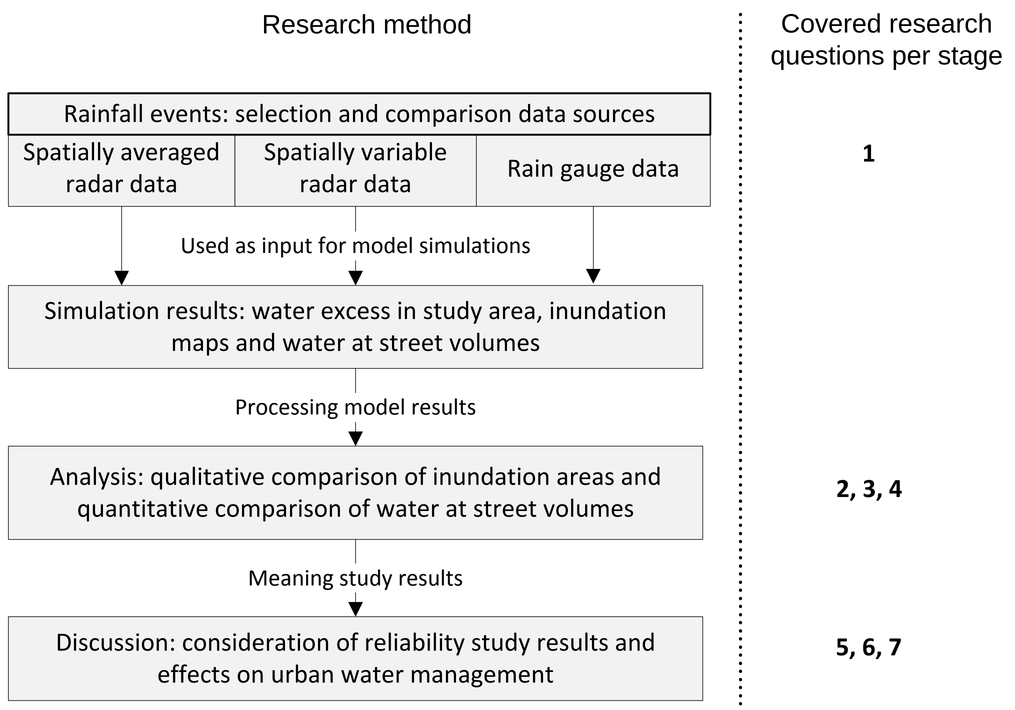


Figure 1-3: Schematization of the stages in the research with accompanying relation to the research questions.

1.6.2 Outline

An outline for the structure and global contents of the master thesis report is given as follows. In chapter 2 all the data sources that constitute input for the study are described. Besides, an introduction to the case study will be presented. Chapter 3 continues on the gathered rainfall data of the study area in order to select useful events for the modelling. Therefore, information of radar and rain gauge data since 1998 are evaluated and the differences between the areal rainfall of radar and rain gauge are revealed. Furthermore the method for comparison for the different rainfall data sources is explained.

The urban surface runoff model is subject of chapter 4 in which its backgrounds, workings and assumptions are considered. Also the important, influential parameters of the model are explained. After the simulation of the rainfall events in the surface runoff model, the results are given in chapter 5. The research questions with respect to the model simulation outcomes and their differences are clarified within this chapter.

Hereafter, chapter 6 proceeds with notable aspects for discussion, which include the reliability of the study results and the possible implications for urban water management. Finally, the answers to the research questions are summarized in the conclusions of chapter 7. In addition, some recommendations for urban water management and future study subjects are provided within this chapter.

2 STUDY AREA & DATA

In this chapter, first the case study is described and hereafter the several data sources for the study are presented. This information consists of rainfall data from historical weather radar images as well as time series of rain gauge stations. Subsequently, the area characteristics are introduced, such as the elevation map for the surface runoff modelling. The last paragraph describes the area expert information concerning known water at street situations.

2.1 Study area

2.1.1 Urban case study of Amersfoort

To investigate the effects of weather radar application on the urban water management, the city of Amersfoort will be used as study area. The most important reason for this choice is the existence of a current project called 'HydroValley' in which HydroLogic is participating in a public-private partnership between Water Board 'Vallei en Eem' and some municipalities among which Amersfoort. As a result of heavy rainfall events, the urban area copes with many sewage overflows that need to be reduced to improve the quality of surface waters. However, the reduction of sewage overflows will not solve the problems of water at street and might even make those inconveniences more frequent. Therefore, the efficiency of the urban surface drainage needs to be enhanced.

The objective of the cooperation in the project is to avoid structural measures, like renewing the sewage infrastructure, preferably by finding optimization measures above the surface to retain peak intensities of rainfall. In this way, the investments for the improvements to the urban drainage system could be more efficient and nuisance as a result of drastic structural interventions could be spared. Due to this project, specific knowledge and information is available at HydroLogic and assistance at the thesis subject can be optimal.

The selection for the case study of Amersfoort is further motivated by the elements described below:

- The rainfall-runoff model for the case is available for use of spatially averaged rain gauge data. Input of weather radar data is possible with some model adjustments. For the chosen case study, the basis of the rainfall-runoff model is available. However, initially the reliability of the results was questionable. Therefore, some development of the model is included in the study and several model adjustments are implemented.
- Rainfall in the area of Amersfoort is to a great extent determinative for the water management measures in that area. This is explained by the following aspects:
    - The drainage of storm water in Amersfoort is strongly affected by many variations in altitude within the urban area. This fact in combination with high percentages paved surface in the urban area often causes inconvenient situations during extreme rainfall events. In these cases, sewage surpluses that appear as water at street create flow paths of water to the low-lying areas. Here the confluence of water streams can cause bottlenecks with inconveniences and possible damages.

- Water inconveniences due to groundwater problems are of little importance in the model area. Also, discharges from upstream in the catchment do not affect the city of Amersfoort.

2.1.2 Model area in Amersfoort-Zuid

A rainfall-runoff model has been developed for the southern part of Amersfoort (see Figure 2-1). In this part of the city, most variations in altitude are present which can cause accumulation of surface runoff and accompanying water at street situations.

Figure 2-1: The location of the study area (black box) in Amersfoort. The surface of the model area is 12.5 km^2.

Rainfall input information for the surface runoff model will be supplied by rainfall information from weather radar as well as from rain gauge measurements. In the next paragraphs, these rainfall data sources will be further explained.

2.2 Weather radar

For the model area in Amersfoort, several rainfall events are identified to serve as model input. The identification has been performed based on the presence of heavy rainfall events with specified extremeness in the weather radar data series (further explained in paragraph 3.1.1). In the Netherlands these radar data are available since 1998. Therefore almost thirteen years of rainfall data have been analysed for this study. In the following paragraph some important characteristics of the weather radar in this period are described.

2.2.1 Spatial and temporal resolutions

The Dutch meteorological institute (KNMI) provides weather radar data from the stations in De Bilt and Den Helder. Until 2009, the radar rainfall information was provided per hour with a spatial resolution of 2.5 kilometer. This results in the radar grid for the study area as displayed left in Figure 2-2.

Since the beginning of 2009, the temporal resolution has been upgraded to 5 minutes and the spatial resolution to 1 kilometre. The implication for the radar grid in the model area is shown right in Figure 2-2. It is particularly this development that brought weather radar into prominence for urban water management.

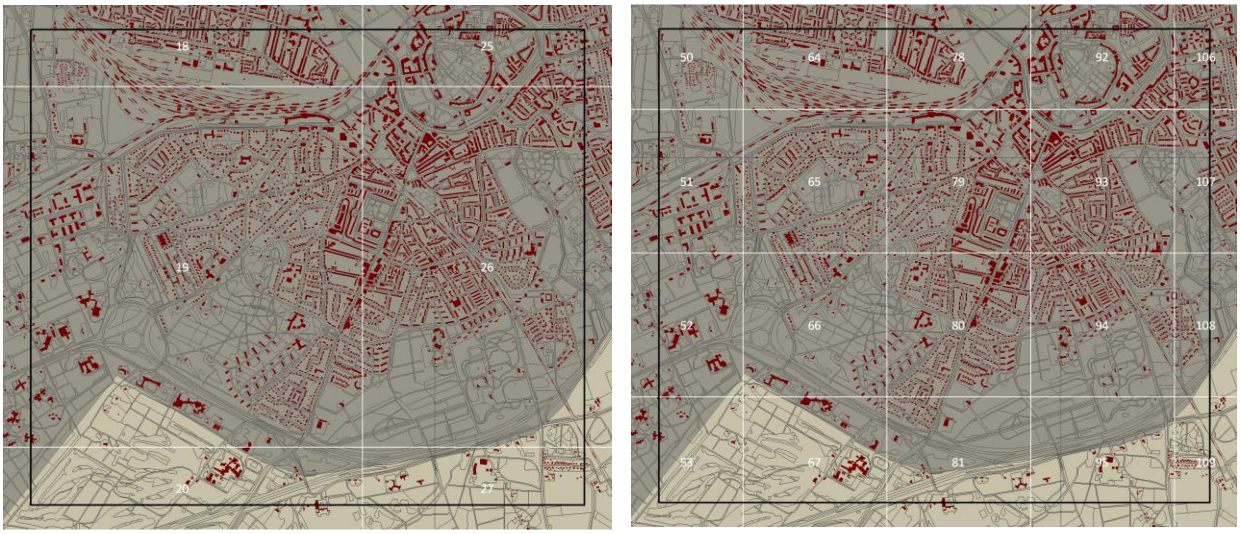


Figure 2-2: The 2.5 km radar grid (left) and the 1 km radar grid (right) for the model area (black box) in southern Amersfoort.

2.2.2 Availability of corrected radar data

The radar data series can be analysed via software of Hydrologic which makes calibrated weather radar data of the KNMI available. This radar data is adjusted with rain gauge information in order to reduce the error sources in the raw radar data. Important aspects with respect to the uncertainty of radar observations are described in Appendix B. The point measurements of rain gauges are assumed to be accurate while radars are capable to deliver detailed spatial rainfall structures (Overeem, 2009). For that reason, the distributed radar data of the KNMI have been corrected with rain gauge data. The method makes use of a correction field by making a distance weighted interpolation from daily rainfall depths of rain gauge stations. Subsequently, the correction field is obtained by dividing the rain gauge rainfall image by the rainfall image of the raw radar data. In an additional calculation, the hourly rain gauge stations are used to correct for systematic errors in the rainfall image of raw rain gauge data. This way, the daily radar rainfall estimate which overlaps the location of the rain gauge has been set equal to the corrected value of the gauge itself (Overeem et al., 2009). With this correction, the spatial variability of the radar data is preserved, while the structural underestimation is removed from the data.

The hourly radar data from 1998 until now is available via a software package called HydroNet. This program has a specific extension in ArcMap to display the radar rainfall maps of the Netherlands and for smaller areas like the radar pixel raster of Amersfoort. This visual representation in ArcMap is suitable to represent the spatial variability of the different rainfall events at a glance.

The weather radar data for the urban area of Amersfoort since 2009 can be acquired by means of HydroNet Urban. An agreement with HydroLogic gives municipalities the license to access these radar rainfall data with information for their own urban area. In this way, the radar data for specific events of various durations can be retrieved. HydroNet Urban shows for example maps of the city with the radar rainfall images of 5 minutes or the cumulative rainfall of 1 week.

2.3 Rain gauges

Besides weather radar information, rainfall data from rain gauges is available. These rain gauge data can be divided into measurements from the official measurement stations of the KNMI and rain gauges of municipalities for local applications. In the next paragraphs, the available rain gauge data for the surroundings of Amersfoort will be explained.

2.3.1 Automatic rain gauge station of the KNMI

Official rainfall information of rain gauges is provided by the automatic and manual measurement stations of the KNMI. The 36 automatic stations in the Netherlands, corresponding to approximately 1 station per 1000 km^2, provide hourly precipitation information (KNMI, 2010). Historical rain gauge data in the surroundings of Amersfoort are provided by the automatic stations in De Bilt and Soesterberg (see Figure 2-3). However, nowadays only the weather station in De Bilt is operational as the automatic station Soesterberg has been out of operation since mid-November 2008 (KNMI, 2010).

Figure 2-3: Automatic weather stations of the KNMI in the surroundings of Amersfoort.

In addition to the automatic rainfall stations, the KNMI provides rainfall information of manual rain gauges. An advantage of the manual rain gauge network, with 325 stations in the Netherlands, is the ten times higher density in comparison to the automatic rain gauge network. However, the manual stations only give information of 24h cumulative rainfall. Therefore, these data are less appropriate for the analyses of rainfall events in urban areas with characteristic small timescales up to a few hours. For the period 1998 through 2008, the point measurement data of the automatic rain gauge in Soesterberg will be used to compare to the weather radar data. In consequence of the large distances between the available automatic rain gauges in the vicinity of Amersfoort, no interpolation techniques between the measurements of different stations will be applied.

2.3.2 Rain gauges of municipality Amersfoort

Besides the weather stations of the KNMI, a number of five rain gauges in Amersfoort became operational in autumn of 2008 with a temporal resolution of 5 minutes. In addition to the data of the KNMI, these automatic rain gauges provide one point measurement of the precipitation inside the study area and a few observations close to the study area. However, the reliability of these rain gauges is uncertain as the positioning in the urban area does not meet all the requirements for accurate measurements (KNMI, 2000). The picture in Figure 2-4 shows the setting of rain gauge Amersfoort-Zuid with its positioning close to an apartment block. The rain gauge is centrally situated in the study area where its location corresponds to radar pixel 79 as shown in Figure 2-2.

Figure 2-4:
Rain gauge Amersfoort Zuid.

A comparison of available 9 months rainfall depths of the urban rain gauge and several KNMI stations may provide insight in the accurateness and reliability of the rain gauge measurements. The results are presented in Table 2-1.

Table 2-1: Rainfall depths for the period January – October 2009.

Rainfall station	Rainfall accumulation (mm)	Percentage difference with respect to gauge Amersfoort Zuid
Rain gauge Amersfoort Zuid	624.1	--
Automatic station De Bilt	572.5	-8.3%
Automatic station Lelystad	598.3	-4.1%
Automatic station Cabauw	484.9	-22.3%
Manual station Soest	608.3	-2.5%
Manual station Hamersveld	619.4	-0.8%

Based on the table above, it appears that even on the long time span of nine months, the range in rainfall depths can be wide and spatially distributed. The rain gauge stations nearest to Amersfoort, the manual stations of Soest (approximately 5 km west of the model area) and Hamersveld (approximately 1 km east of the model area), have the smallest deviating rainfall depths. Their differences are within 2.5 percent. Therefore, it is concluded that the rainfall observations of the rain gauge Amersfoort Zuid are sufficiently reliable at large timescales. In addition it is assumed that the use of its data can be permitted for short time scales in this study.

2.3.3 Overview of rainfall data sources

In Table 2-2, an overview is given of the various sources of rainfall information and the way they will be compared hereafter. This comparison will be done for both the rainfall information in the model area and the simulated water excess situations in the final model results.

Table 2-2: An overview of the rainfall information sources that will be used for comparison.

Period	Radar data	Rain gauge data
January 1998 – December 2008	Hourly radar data, 2.5 x 2.5 km	Hourly station data Soesterberg
January 2009 – August 2010	5 minute radar data, 1 x 1 km	5 minute rain gauge data of municipality Amersfoort

A further explanation of the method applied for the comparison of radar and rain gauge information in the rainfall-runoff model is given in chapter 3.

2.4 Areal data rainfall-runoff model

Next to the rainfall data, information of the model area is required to enable the surface runoff modelling. Besides the parameters of the sewage system, described in paragraph 2.5, the altitude and land use are of major importance.

2.4.1 Elevation map

The part of the rainfall that cannot be discharged towards the sewage system is recognised as water excess. This amount of water contributes to the surface runoff which is dependent on the slope of the surface and thus on the elevation differences in the area. These altitudes in the model area are available from the elevation database of the Netherlands (AHN). It consists of a raster map with altitude values with a resolution of 5 * 5 m and will serve as condition for the model simulations. In Figure 2-5, the map of the AHN is represented for the study area.

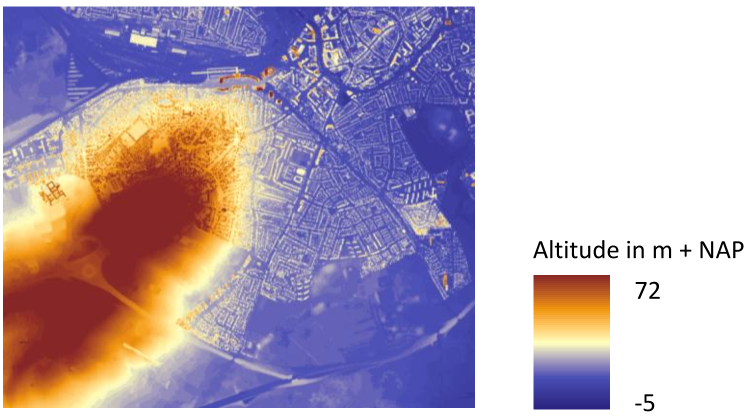


Figure 2-5: Elevation map of the model area in the southern part of Amersfoort.

The maximum altitude is 72 m above the Amsterdam Ordnance Datum (NAP), which is located on top of the area "De Berg". This is the west and south-western part of the model area. The low lying areas are situated in the eastern part of the model area with a minimum altitude of 5 m below NAP.

During the graduation period, the successor of AHN1, AHN2 has already been introduced for several areas in the Netherlands. Unfortunately, the updated altitude information for Amersfoort has not been released on time and could not be used for this study. From 2011, the more accurate elevation maps will become available. Several errors existing in AHN1 will be removed or diminished, such as those from incorrectly represented buildings, viaducts or trees.

2.4.2 Land use map

The infiltration rates of the storm water differ for the various land use types in the urban area. Therefore a map with nominal land use classes (Amersfoort, 2010) is included in which six different types have been discerned (see Figure 2-6). This map is coupled to a table in which the infiltration rates for the land use classes have been defined. The determination of these infiltration rates is part of the model calibration that is described in chapter 4.

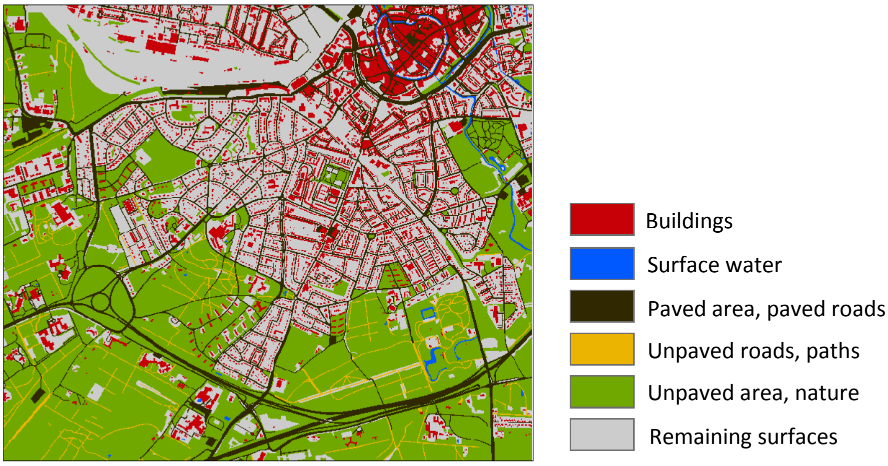


Figure 2-6: Land use classes for the model area.

2.5 Area expert information

Detailed information on the capacities and working of the sewage system of Amersfoort is not available. Furthermore, some information concerning the prominent water at street locations in the study area are relevant for comparison with model results in order to check its performance. Therefore, a meeting with two area experts from the city of Amersfoort was organized (Lensink & Van 't Klooster, 2010). Their experience and knowledge provided input for the study.

2.5.1 Sewage system characteristics

Initially, the assumptions for the properties of the combined sewage system are the general values of 7 mm for the storage capacity and 0.7 mm/h for the sewage discharge towards the waste water treatment plant (Leidraad Riolering, 2009). However, the sewage system of Amersfoort has a specific response which is caused by the variations in altitude and several measures that have been implemented in the past years.

First of all, the slope of the terrain in and around “De Berg” causes the water in the sewage system to discharge quickly to the lower grounds. Pumping is not needed in this area as the water discharges under free fall in the direction of the city centre before it continues north-westward. In the low lying areas, the storage capacity of the sewage system is hampered by the large volumes of water from “De Berg”. Therefore, the most serious water excess problems have arisen at the edges of the area “De Berg”. During heavy rainfall events, the quick sewage discharge accumulates in the areas at the foot of “De Berg” and often causes water at street due to rising manhole covers. The occurrence of this type of water at street should be separated clearly from that caused by surface runoff, where only the latter is subject of this study. In the identification of water at street locations, the area experts have made the distinction of several causes of water at street as clear as possible. Besides, the frequency of contaminated water at street from the sewage system reduced significantly in the last few years as a result of the construction of additional sewage storages.

2.5.2 Water at street history and implemented measures

The following water at street locations have been indicated by the area experts (see also Figure 2-7 on the next page):

1. Surroundings of the “Stationsplein” as a result of surface runoff due to the high percentage of paved surfaces.
2. Surroundings of the “Utrechtseweg” at the intersection with the “Kersenbaan”. At this location, the railway has been heightened which creates a barrier in the water flow path. Furthermore, water at street situations as a result of rising manhole covers used to take place. However, the problems seem to be diminished or even solved by means of the additional sewage storage and infiltration facilities.
3. Surroundings of the “Leusderweg” at the intersection with the “Kersenbaan”. This is caused by both the surface runoff and sewage system problems. Also at this location, the inconveniences have been decreased due to the implemented measures.
4. Surroundings of the “Gerard Doustraat” due to surface runoff.
5. Surroundings of the “Utrechtseweg” at the intersection with the “Stadsring”. This water at street situation is only caused by the rise of water from the manhole covers.

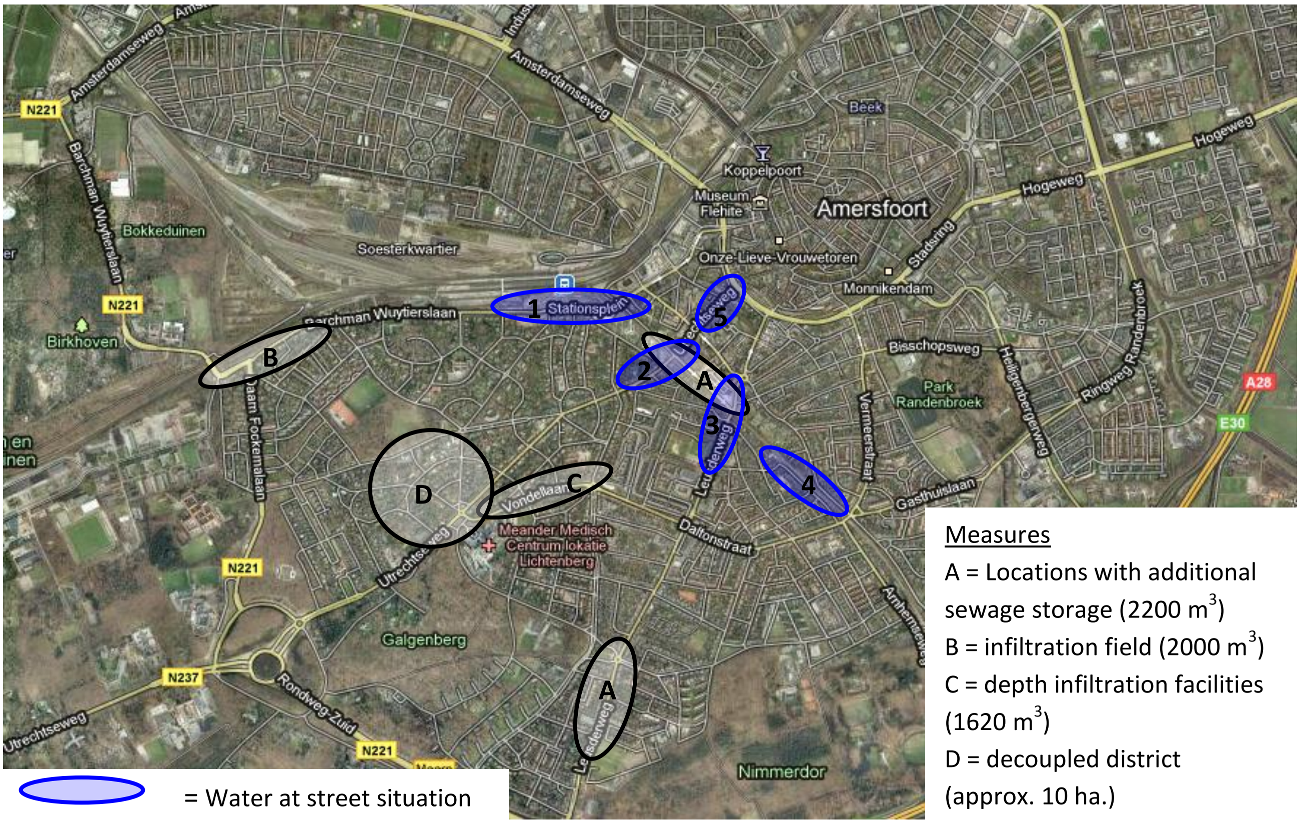


Figure 2-7: An overview of water at street locations and measures to the sewage system, as identified during the session with area experts

Since 2000, several measures have been implemented in the sewage system of Amersfoort to challenge the inconveniences of water at street. Especially those problems caused by contaminated water at street from the sewage have been tackled. The quick discharge of water via the sewage system from the area "De Berg" can be stored in the following facilities (Figure 2-7):

A. Additional sewage storages at the "Kersenbaan (1,000 m^3 since 2000) and the "Leusderweg" (1,200 m^3 since 2001). Until two days after heavy rainfall events, the area experts have observed that the additional storage facilities could not be drained on the sewage system, because the water level in the pipes still have not fallen sufficiently in that area. This should be taken into account for events that happen in quick succession.
B. A retention basin with infiltration field at the Barchman Wuytierslaan (2,000 m^3/ 3,800 m^2 since 2004). The water at street problems in that area are nowadays supposed to be negligible as no problems have been reported since then.
C. Two deep infiltration facilities around the "Vondellaan / Van Campenstraat (1620 m^3 since 2010). These infiltration facilities are especially meant to store the storm water discharge from the district "Lichtenberg".
D. In district "Lichtenberg", the front sides from approximately 75% of the roofs have been decoupled.

The current policy of the city of Amersfoort is to restrict the water at street problems as much as possible. In general this implies that water at street situations cannot be prevented. Actually, these water at street situations are not experienced to be very inconvenient as the citizens expect some degree of water excess during extreme rainfall. Nevertheless, serious water inconveniences and damages should be prevented, such as inundation inside buildings.

3 RAINFALL SELECTION & METHOD FOR COMPARISON

The rainfall data are the main input for the rainfall-runoff model. In this chapter, the data series of radar since 1998 are examined to identify appropriate events for the model simulations. The selection of events is first made on the basis of extremeness and further elaborated by the spatial variability in the study area. Next to this, an overview will be presented of the rainfall data sources and the comparison method in this research. With help of this chapter, sufficient information is provided to answer the following research question:

1. *To what extent does the total rainwater volume in the study area for the identified events of the weather radar data and rain gauge data correspond to each other?*

3.1 Identification of extreme rainfall events

First, a selection of rainfall events is made on the basis of extremeness. Consequently, the heaviest events that have resulted in water at street situations will be included in the study. Within the selected events, several degrees of water at street will be present, varying from some water at street locations to extensive water inconveniences. Subsequently, a further selection is carried out on the basis of spatial variability of rainfall. Particularly events with considerable spatial variability will be taken into consideration in order to study the effect of the spatial variability in the radar data on the water excess simulations. The radar data have functioned as basis, implying that for the identified events in the radar data, the rain gauge data for the corresponding period have been gathered.

3.1.1 Selection on the basis of extremeness

Based on a quick scan of possible extreme rainfall events in the radar data since 1998, some criteria have been set to obtain sufficient model input events. For the hourly radar information from 1998 up to and including 2008, an analysis is performed on the basis of the statistics for extreme rainfall (seeTable 3-1) in the urban area of the KNMI (Smits et al., 2004; Buishand & Wijngaard, 2007).

Table 3-1: Rainfall statistics (in mm) of short durations for urban water management.

	minutes				hours				
	5	15	30	60	2	4	6	8	12
10 x per year	-	3	4	5	7	9	11	12	13
5 x per year	-	4	6	7	10	12	14	15	17
2 x per year	4	6	8	10	13	16	19	20	23
1 x per year	5	9	11	14	17	21	23	24	27
1 x per 2 year	7	11	14	18	21	25	27	29	32
1 x per 5 year	9	15	19	23	26	31	34	36	40
1 x per 10 year	11	18	23	27	31	36	39	41	46
1 x per 20 year	12	21	27	32	36	41	45	47	52
1 x per 50 year	15	26	32	38	42	49	53	56	61
1 x per 100 year	17	29	37	43	48	55	59	62	68

In the surroundings of the model area in Amersfoort (Figure 2-1), the events have been selected if in at least one radar pixel the

- 1 hour precipitation exceeds 14 mm (return period of 1 year), or if the
- 4 hour precipitation exceeds 25 mm (return period of 2 year).

It should be mentioned that the sewage system was designed to cope with rainfall events with a return period of 2 year. Due to bottlenecks in the sewage system, water inconveniences are supposed to arise locally even during the less extreme criterion of the hourly event (see problem areas in section 2.5). The choice for the selection of more extreme events in the latter criterion arises from the fact that especially heavy rainfall events of short duration are normative for the urban area due to the quick runoff on paved surfaces (Buishand & Wijngaard, 2007). Therefore it is assumed that events of longer duration should be more extreme to result in water inconveniences.

Since 2009, the information of the rainfall events is much more extensive in time as well as in space. Therefore the course of a single rainfall event can be analysed in more detail and the duration of the specific selected events can be fitted more precisely to their real lengths. In the extreme event tool in HydroNet Urban, events in this period with cumulative rainfall of more than 10 mm in 75 minutes can be displayed. This criterion results in rainfall events for the urban area of Amersfoort that possibly meet the criterion of 14 mm/h within the model area. After analysis of these events, only those that satisfy the 1 hour criterion have been remained. In addition, the radar time series from the beginning of 2009 have been investigated on the existence of events that exceed the 4 hour criterion. Finally, the identified rainfall events with respect to the extremeness since 2009 (5 events) together with those from 1998 through 2008 (16 events) have been listed in appendix C. It should be mentioned that the extremeness criteria are used in a directive way and that some events with deviant durations are also selected, in particular August 26 2010 with a selected duration of 12 hours.

The list confirms the fact that the extremeness of rainfall is dependent on the season of the year. This means that less extreme rainfall events occur in the period December through April. The annual maximums of short durations (up to a few hours) mainly take place in the summer showers of July and August. For events of longer durations, the annual maximums are more evenly distributed. These events mainly occur from July to October inclusive (Smits et al., 2004).

3.1.2 Selection on the basis of spatial variability

So far, the selection of rainfall events has been based on the extremeness of the rainfall accumulation in one or more radar pixels. However, the events that show a uniform rainfall pattern in the model area are not the most interesting ones for the comparison of uniform and spatially variable rainfall data and its propagation in the water at street simulations. Nevertheless, the assessment of rainfall events with various degrees of spatial variability, including some with little variability, may reveal more clarity regarding the effects on the model results. This paragraph will focus on the spatial variability of the preselected events in order to make a further selection that is appropriate for modelling.

The spatial variability of the rainfall events is examined with the help of the coefficient of variation, as it is expressed in a dimensionless value. Therefore, the coefficient enables the comparison of data with varying means, which is the case for the identified rainfall events. The equation of the coefficient of variation is as follows (Jensen & Pedersen, 2005):

$$C_v = \frac{S}{\overline{X}} = \frac{\sqrt{\frac{1}{n-1}\left[\sum_{i=1}^{n} x_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)^2\right]}}{\frac{1}{n}\sum_{i=1}^{n} x_i} \qquad \text{(eq. 3.1)}$$

With S = standard deviation
$\overline{X}$ = mean of radar pixels (average in the model area)
x_i = rainfall amount in radar pixel i
n = number of radar pixels

The coefficient of variation expresses the standard deviation as fraction of the mean. A large spatial variability is represented by a large coefficient of variation.

Prerequisite for application of this formula is that the data are normally distributed (in this case the variance is independent from the mean). In an analysis, a plot was made of variance against the mean and no clear relationship between the variables was found. Therefore, it is assumed hereafter that normal statistical methods can be used as in Pedersen et al. (2010).

Based on the calculation of the coefficient of variation for the radar pixels inside the model area, it is possible to judge whether an event is of interest for this study. If the spatial variability in the radar data is small, the difference between the model input of uniform rain gauge data and spatially variable radar data does not originate from the spatial variability. In these cases, the radar input is almost uniform in space as well and the effect of spatial distribution in rainfall cannot be assessed, which is the main objective of this study. However, it should be noted that the accumulated uniform value of the rainfall depth may differ between the radar and the rain gauge observation as both the measurement location and the method of measurement differ.

A criterion is set over which the rainfall events can be characterised as variable in space. Below this threshold, the events will be marked uniform or little variable in space. As the focus in this study is on the spatial variable events, most of the events with a uniform pattern will be eliminated from the selected event list. Only a few will remain to explore the differences between radar data and rain gauge data in rainfall events with uniform patterns.

Due to the changing pattern of rainfall events with increasing duration and mean rainfall depth, the criterion for spatial variability in the 4 hour events will be used differently compared to the 1 hour events. This can be clarified with the help of Figure 3-1 in which the coefficients of variation are plotted against the mean rainfall accumulations over 1 and 4 hour events. The figure indicates correlation between the mean rainfall depth and the spatial coefficient of variation, since the coefficients clearly decrease for increasing rainfall depths. This is probably caused by changing rainfall patterns with increasing rainfall depths. Moreover, the seven events with the highest mean rainfall depths consider 4 hour events, which generally show more gradual changes between the different radar pixels. Summarizing, it may be stated that a relation exists between the temporal and the spatial scale of the rainfall events.

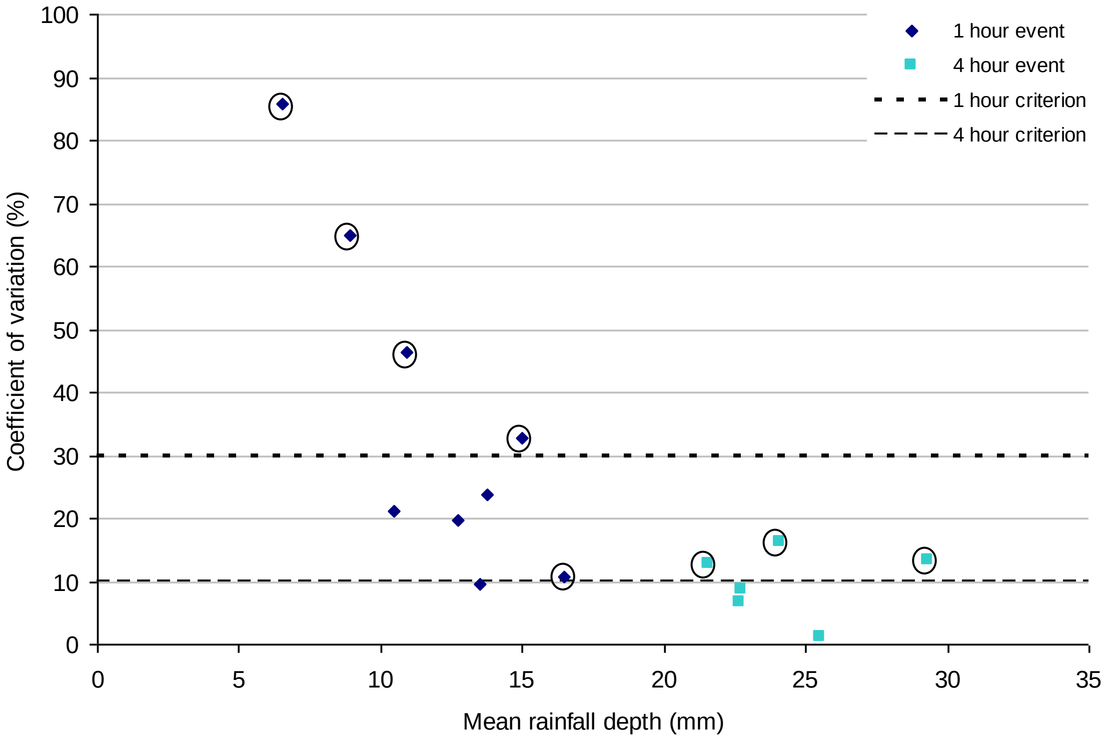


Figure 3-1: Coefficient of variation plotted against the mean. The circled dots represent the selected events that are included in Table 3-2.

For the 1 hour events the coefficient of variation is distinctly higher in four cases as can be seen in Figure 3-1. These events exceed the C_v value of 30%, which is regarded as threshold. By employing this threshold, a suitable number of events is obtained for the model simulations. Besides the events selected on the basis of their coefficient of variation, the event of the 3rd of June 2008 is included in the research. This event has been added to consider the differences of quite uniform radar rainfall observations versus measurements of the automatic station Soesterberg some kilometres away.

The coefficients of the 4 hour events are situated more closely to each other. Given the restricted spatial variability in the 4 hour events, a score for the C_v over 10% has been set to perform the further selection. In this way, also a numerical balance between the rainfall events with the 1 hour or 4 hour duration is preserved. More details of the selected events can be found in Table 3-2.

Table 3-2: Selected rainfall events on the basis of spatial variability for the period 1998-2008.

Event date	June 15 1998	July 29 2000	August 7 2001	July 28 2006	July 28 2006	July 5 2007	June 3 2008	Sept. 12 2008
Duration (h)	1	1	1	4	1	4	1	4
Rainfall (mm) in radar pixel*								
18	15.3	19.0	19.7	32.7	16.8	20.0	17.3	19.6
19	11.7	12.2	17.0	30.9	8.1	24.3	18.1	23.4
20	4.6	4.1	9.2	24.6	7.7	27.2	16.4	25.6
25	3.4	6.5	16.8	34.0	18.0	19.3	16.7	18.5
26	2.6	7.8	18.8	28.8	8.0	24.7	17.2	19.6
27	1.6	3.9	8.4	24.9	6.8	29.2	13.0	22.8
Mean (mm)	6.5	8.9	15.0	29.3	10.9	24.1	16.5	21.6
St. deviation (mm)	5.6	5.8	4.9	4.0	5.1	3.9	1.8	2.8
Coefficient of variation (%)	85.8	65.0	32.8	13.5	46.5	16.2	10.9	12.8

* See Figure 2-2 for a map with the radar pixel raster.

Correspondingly, the coefficients of variations have been calculated for the events of 2009 and 2010. These outcomes cannot be compared with those presented above as the value is based on twenty radar grid cells instead of six. Therefore, the spatial scale of the data is different and the standard deviation of the radar pixel values may be affected significantly. In case more rainfall depths are close to the mean, this could indicate gradual changes of rainfall depths in space. On the other hand, some small scale areas with deviant rainfall depths may appear as well. The results of the analysis for the 2009 and 2010 events are represented in Table 3-3 and Figure 3-2 below.

Table 3-3: Assessment of spatial variability in the selected rainfall events for 2009-2010.

Event Date	Duration [minutes]	Mean rainfall depth [mm]	St. deviation [mm]	Coefficient of variation [%]
May 26 2009	90	14.9	4.0	27.1
August 28 2009	240	22.9	1.6	7.1
July 10 2010	180	32.2	5.1	15.9
August 4 2010	60	11.1	1.8	16.4
August 26 2010	720	40.5	3.6	8.9

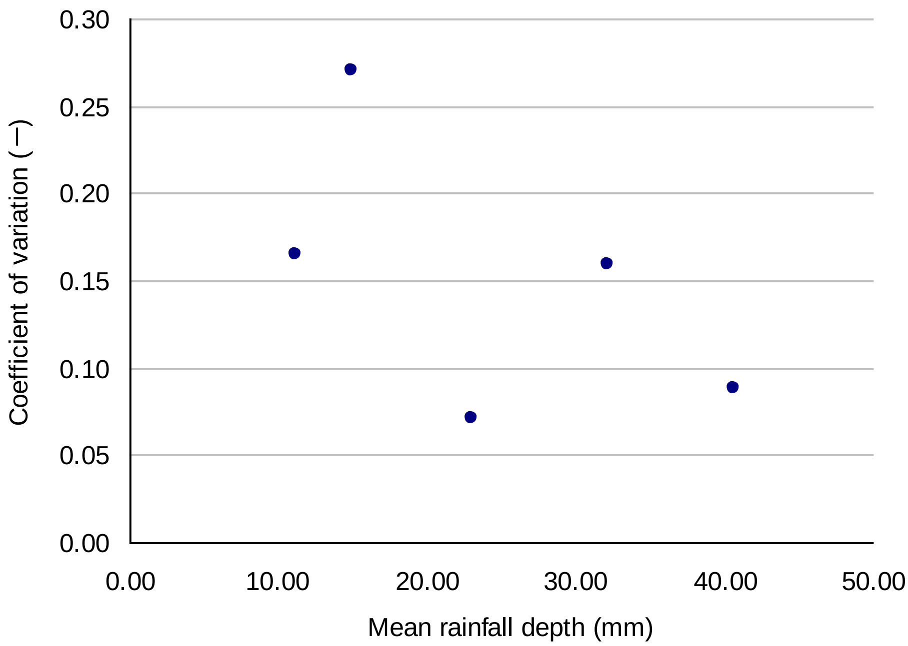
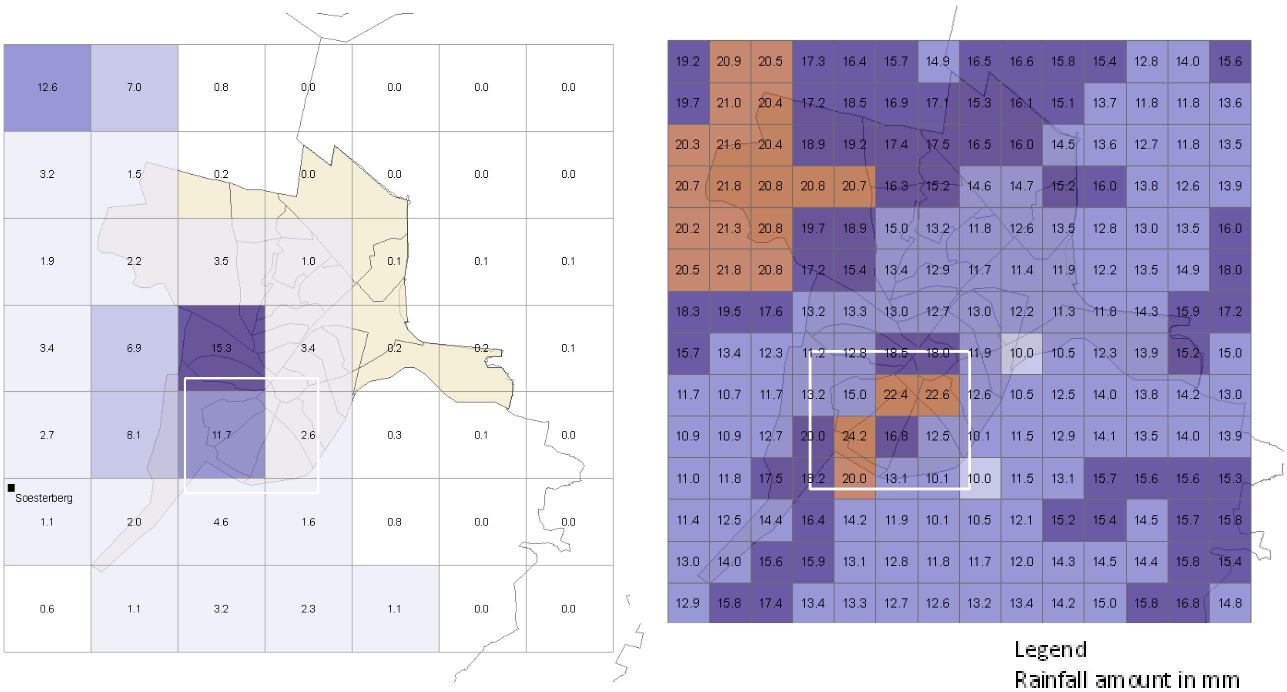


Figure 3-2: Coefficient of variation plotted against the mean for the selected events in the period 2009–2010.

The events are difficult to compare since their durations vary a lot. In principal the events with the increased spatial and temporal resolutions of the weather radar are all more interesting for assessment with the model if compared to the period 1998-2008. Therefore, the five events that have been selected for 2009-2010 on basis of their extremeness will all serve as input for the rainfall-runoff model in addition to the selected events of Table 3-2.

3.1.3 Radar & rain gauge model input

From all the selected rainfall events, the cumulative rainfall maps of the radar data are enclosed in appendix D . The maps give a clear view of the spatial variability in the weather radar data. As an example, the rainfall accumulation map of the event on June 15 1998 is represented left in Figure 3-3. In comparison, the rainfall event on May 26 2009 is depicted at the right side. Here, the effect of increased spatial resolution of the weather radar is clearly revealed.



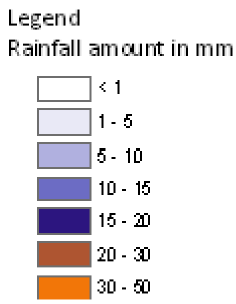


Figure 3-3: Rainfall accumulation maps of the events on 15 June 1998 (left) and 26 May 2009 (right) with the model area represented by the white box.

As already mentioned, the accompanying rain gauge data of the selected events have been collected from the data series of the KNMI and the city of Amersfoort. These rain gauge data are listed in Table 3-4 for all the events that will be used for the model simulations. For a comparison of the total rainfall in the model area between radar and rain gauge input, also the spatially averaged rainfall of the radar input has been calculated (see Table 3-4). The latter is calculated on the basis of the arithmetic average of the radar pixel rainfall depth (total water volume in the model area divided by the surface). Besides the spatially distributed radar data and the rain gauge data, the spatially averaged radar rainfall data will be one of the three input sources for surface runoff modelling.

Table 3-4: Spatially averaged radar and rain gauge rainfall depths corresponding to the selected radar events.

Rainfall event	Mean radar rainfall depth (mm)	Rain gauge rainfall depth (mm)	Rain gauge station
August 4, 1998	7.8	9.0	Soesterberg
July 29, 2000	14.7	43.1	Soesterberg
August 7, 2001	22.1	12.7	Soesterberg
July 28, 2006	29.8	0.0	Soesterberg
July 5, 2007	27.3	16.4	Soesterberg
June 3, 2008	21.4	16.6	Soesterberg
September 12, 2008	24.0	42.2	Soesterberg
May 26, 2009	16.0	18.4	Amersfoort Zuid
August 28, 2009	23.1	23.2	Amersfoort Zuid
July 10, 2010	37.8	35.5	Amersfoort Zuid
August 4, 2010	11.6	9.0	Amersfoort Zuid
August 26, 2010	40.5	67.8	Amersfoort Zuid

3.2 Comparison method of rainfall sources

The rainfall data identified in the previous paragraph will be the basis to study effects of spatial variability in radar data compared to rain gauge information. This paragraph pays attention to the method for comparison between the weather radar and rain gauge model results.

The model output in terms of possible water at street situations will be compared for the different input sources of every single rainfall event. The method for this assessment is represented in the schematization of Figure 3-4 and further explained below.

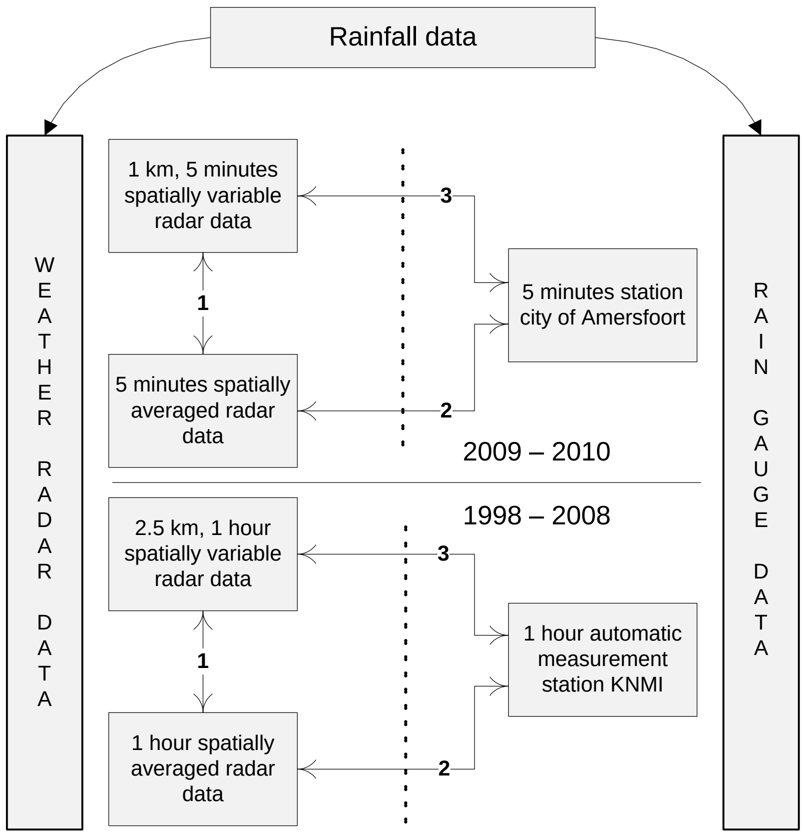


Figure 3-4: Method for comparison between the various rainfall data sources.

The model output will be compared for the following pairs of rainfall data sources:

1 The spatially variable radar data versus the spatially averaged radar data. The comparison of the two radar data sources is intended to examine the effect of the spatial variability on the simulated water excess. Since the total rainwater volume in the model area is equal for the compared model runs, this comparison is most appropriate to reveal differences caused by the spatial pattern of the event.

2 The spatially averaged radar data versus the rain gauge data. This comparison is aimed at the assessment of rain gauge point measurements in relation to spatially averaged radar data that is based on observations in the whole model area. It may clarify the consequences of the observed total rainfall volume in the model area by the radar in comparison to the amount expected on the basis of a point measurement. In the period 1998 through 2008 the rain gauge measurements were taken a few kilometres outside the model area. For this time span, the comparison can prove whether the location of the measurement is responsible for significant differences in rainfall input and resulting water excess simulations.

3 The spatially variable radar data versus the spatially averaged rain gauge data. The aim of this comparison is the investigation of the effect of both the spatial variability in the radar data and the difference in total rainfall between point measurements of the rain gauge and spatial measurements of the radar. It is interesting to notice how the analyses of 1 and 2 reveal themselves in this comparison.

4 RAINFALL-RUNOFF MODEL

In this chapter, first the structure and working of the used model are explained. Furthermore, a sensitivity analysis and a calibration are carried out to process the surface-runoff model for the simulation of the selected rainfall events from the previous chapter. In order to optimize the model working for the purposes of this study, the various parameter values are assessed and also adjusted to approach a realistic situation. Therefore, the area expert information of historical events and the urban drainage characteristics will be guiding for the estimation of appropriate model settings.

4.1 Model description

For rainfall-runoff modelling it is important to understand the specific characteristics of the urban area. Especially the large, impervious surfaces like roads or brick pavements need to be considered. In comparison to rural catchments, the following differences can be identified for the water management aspects in the urban catchment (Shaw, 2004):

- A higher proportion of rainfall is appearing as surface runoff, so the total volume of direct discharge is increased;
- for specific rainfall events, the response of the catchment is accelerated which reduces the lag time and time to the discharge peak;
- in general the flood peak magnitudes are increased.

In the surface runoff model, the effect of different kinds of rainfall events on the urban area can be simulated. Its application is particularly appropriate for the simulation of the extent and location of water at street situations. However, detailed processes of the sewage system are not included in the model. Therefore some assumptions have to be made for the rainfall amount that is discharged via the sewage system. This means that only surface runoff can be simulated and that water at street as a result of rising manhole covers is left out of consideration in this study.

The working and the different components of the model will be described in the following section.

4.1.1 Components and structure of the model

The PC Raster model, provided by HydroLogic, consists of several components that need further explanation. The model is composed of raster cells for which specific information about the surface and related information for the drainage of storm water is stored. This is used for the calculation of a water balance with possible water excess. A more detailed explanation of the model is given by means of Figure 4-1, in which its structure is represented schematically. Moreover, it shows the various input data and calculation steps to come to the final water at street maps.

First, several data input files are described, such as the rainfall file, the land use map and the infiltration rate table. All these input files are gathered from a specified folder outside the model itself (see the right column in Figure 4-1).

In the dynamical part of the model where the calculations take place, the precipitation surplus is determined. In order to do so, it is calculated whether the rainfall of the assessed time step will (partly) infiltrate in the surface. Then, the possible infiltration surplus is attributed to the sewage system until the storage capacity is reached. This incorporates the processing of the infiltration surplus together with the sewage storage and discharge parameters for every single raster cell in the model. Finally, this results in the calculation of possible sewage surpluses for all raster cells in the model.

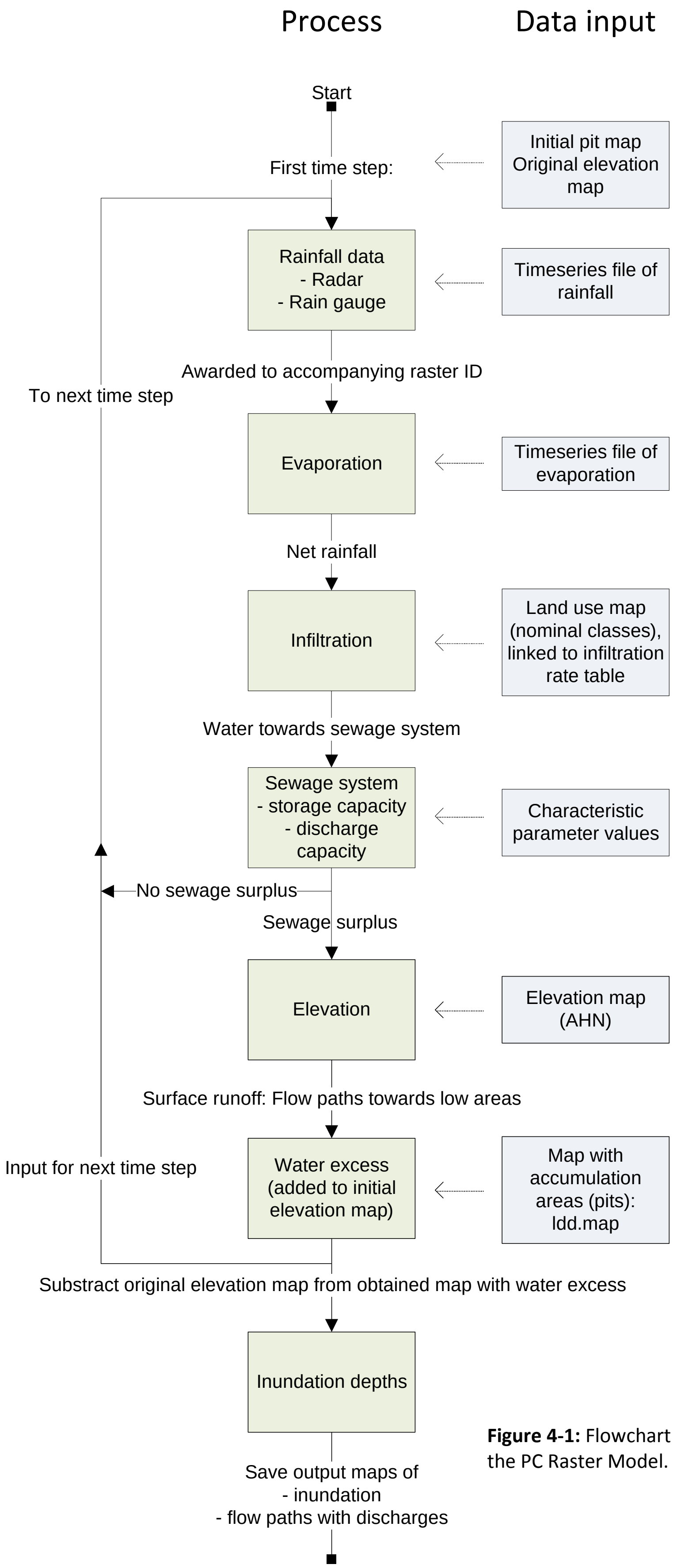


Figure 4-1: Flowchart of the PC Raster Model.

Subsequently, the model will calculate how these surpluses are allocated in the model area by means of surface runoff. This is based on the flow paths in the map with local drain directions (LDD map). All the surface runoff of the treated time step will be directed to the lowest locations in the area (pits) in which the water will accumulate.

Then, a new elevation map is generated in which the water depths in the pits are incorporated. Consequently, the initial pits will possibly not be the lowest raster cells in the new elevation map. Therefore a new LDD map with new pits is created on the basis of the water at street situation at that moment. This LDD map is input for the next time step.

At the end of every time step, the desired output can be reported in for example a map with discharges of water via the flow paths or a map with inundation depths.

The input data are described more extensively below.

4.1.2 Model input data

In the right column of Figure 4-1 the information required for the model calculations is represented. The defined input files consist of:

- Precipitation time series, containing the rainfall amount per time step for a certain area within the model area. This area is given in one uniform map for the spatially averaged data and in a map with the specific radar pixels for the spatially variable input.
- Evaporation time series file which will be linked to the precipitation amounts.
- Land use map (see paragraph 2.4); which is connected to a
- Table with the infiltration rates (see paragraph 4.2.1) for the different land use types.

Hereafter, some input information with characteristics of the model area is specified:

- The elevation map (resolution 5 m *5 m) of the model area based on the AHN (elevation database of the Netherlands, see paragraph 2.4).
- An initial LDD map which contains local drain directions. On the basis of the elevation map, the LDD map prescribes the flow paths of the excess water as well as the locations where the water accumulates (pits).
- Initial storage of the sewage system. Rainfall events that occurred shortly before the start of the model simulation may already have filled up the sewage system to a certain extent. This will result in a decreased storage capacity for the coming rainfall event.

The parameter values of the sewage system can be entered subsequently:

- Maximum sewage storage capacity. The sewage system of Amersfoort is designed for a storage capacity of 7 mm. As mentioned in paragraph 2.5, the construction of additional storage capacities has to be taken into account. Therefore some areas with increased storage capacities are included to represent the subsurface storage in the sewage. Further explanation with respect to the assigned storage parameter values is part of the calibration process in paragraph 4.3.
- Discharge capacity of the sewage system. The sewage discharges the water towards the Waste Water Treatment Plants with a rate of 0.7 mm/h in case of pumping. However, for

the surroundings of "De Berg", the discharges take place under gravity and the velocities are unknown. In the model calibration (paragraph 4.3) is further described how the characteristics of the sewage system are assumed for the water at street simulations.

4.1.3 Model settings

Various settings and assumptions in the model comprise the starting points for the surface runoff simulations. First of all, the temporal and spatial resolution of the model needs to be explained:

- The model is set to use a time step of 10 seconds which means that the model calculates the possible water excess for every 10 seconds of simulated rainfall. This requires the processing of the 1 hour or 5 minute rainfall data by splitting it up into 10 seconds time series files.
- The applied spatial resolution of the model results in raster cells of 5 x 5 m. This resolution has been chosen as it provides the optimal balance between the level of detail in the model outcomes and the required calculation time of the model. Furthermore, it corresponds well with the resolution of the available elevation map. The input of other data sources in the model, such as rainfall or land use type, should be transformed into the same spatial resolution. This way, the spatially variable information for the model calculations is available for every single raster cell.

At some locations or under certain circumstances, some adjustments have to be enforced to the model output in order to disregard incorrect or useless outcomes.

- A buffer zone has been created around the border of the model area to filter accumulation of water in cells that cannot drain through the border. Otherwise, water from the surroundings of the elevated area "De Berg" may accumulate particularly around the low-lying eastern border of the model area. This would result in unrealistic water at street situations. Therefore, a buffer zone of one hundred metres is introduced for which the model output is eliminated from the analysis of the study results. The assessment of interesting water at street locations is not affected as their locations are situated at sufficient distance from the study area border.
- The model has been adjusted to provide maps with inundation depths every simulated minute, so every 6 time steps. In addition, no output will be given if no inundation occurs. This ensures both efficient working of the model and prevents superfluous output in the form of maps.
- The surface runoff that is discharged via the simulated flow paths into the urban surface waters resulted in inundated cells in the model output. Therefore the cells belonging to surface waters like canals and brooks are filtered out of the model output. It is assumed here that no flooding from the surface waters occurs as upstream inflow processes can be neglected in the urban area of Amersfoort.
- A consequence of the model working is the possible unrealistic behaviour during (almost) dry periods in the rainfall events. In reality, a dry period of sufficient length between two succeeding events will cause the inundation depths to decrease or the water at street to disappear. However, once the water is accumulated on the surface in the model simulation, it will remain at the particular location until the final time step. This means that the simulated water at street is not allowed to discharge or infiltrate in later time steps. The cause of this model shortcoming is the elevation map at the beginning of every time step in

which the inundation depths of the previous time steps have been included. Therefore, the model output of situations with rainfall periods that occur in quick succession, should be analysed more carefully. The inundation volumes and surfaces that will be acquired for the long duration events have to be analysed on the basis of the total water at street that have occurred instead of a “final” situation after the last time step. In this way, the simulation will give insight in the total amounts of water that have been allocated as surface runoff for the different input sources.

4.2 Sensitivity analysis

In the first phase of working with the model, a sensitivity analysis is carried out. In general, the analysis gives a feeling of the model response and changes of its parameters. First, it provides insight in the sensitivity of the model results with respect to the various parameters. Parameters with a considerable impact on the output are distinguished. In the development of the model, more attention can be given to these parameters to aim for realistic model behaviour. Furthermore, the results can be translated into possible measures affecting the specific parameter(s) such that it relieves or prevents the water inconveniences. This aspect of the sensitivity analysis is discussed in conjunction with other discussion points in chapter 6.

4.2.1 Framework sensitivity analysis

The sensitivity analysis is carried out with one parameter at a time, while the others are set at their initial value. This univariate analysis has been performed, whereas the simultaneous assessment of multiple parameters would have been too complicated considering the early stage of the model development. Per parameter, two simulations are run; one with a minimum and one with a maximum value (see Table 4-1). Only the evaporation parameter does not have a minimum run since its default value equals zero. Overall, the sensitivity analysis consists of ten model runs including the reference run. The latter makes up the first run in which all parameters have their default value.

Table 4-1: Parameter values for the sensitivity analysis.

Parameter	Values sensitivity analysis		
	Minimum	Default	Maximum
Sewage storage capacity [mm]	5	7	9
Sewage discharge capacity [mm/h]	0.0	0.7	1.4
Infiltration capacity [mm/h]	Depending on the land use type, see Table 4-2		
Pit criterion [m^3]	500	10,000	20,000
Evaporation [mm/h]	0	0	1

Below, the values of the parameters in Table 4-1 will be described briefly and a more elaborated explanation of the infiltration rate parameter will be given.

Sewage storage capacity
As mentioned in the paragraph with sewage system characteristics (paragraph 2.5), the storage capacity of the sewage system in Amersfoort is variable, especially within the model area as a result of the altitude differences and implemented measures. The measures like additional storage facilities are not implemented in the model yet, because of the phase in which the analyses are executed. However, this is not essential as the main objective of the sensitivity analysis is to get feeling with the sensitivity of the parameters. The assumption for the standard model run is the design capacity of 7 mm (Leidraad Riolering, 2009). Variations for the minimum and maximum model run are made by subtracting and adding 2 mm to this value since an increase of 2 mm represents a realistic sewage system measure (Amersfoort, 2008).

Sewage discharge capacity
The design discharge capacity of the sewage system is equal to 0.7 mm/h and set as default value. In rainfall-runoff modelling for short durations in the urban area, the discharge capacity is often ignored (Leidraad Riolering, 2009). Because of local obstructions or accumulations, the discharge capacity can often not be utilised completely. To assess a full obstruction in the drainage of storm water, a value of 0 mm/h has been awarded to the minimum simulation run. On the other hand, the discharge capacity may be much higher in parts of the model area where steep slopes boost the discharge by gravity. Therefore, the value of the maximum run has been doubled to 1.4 mm/h in comparison to the default value.

Infiltration capacity
When the net rainfall collects on the surface, it will infiltrate into the ground at an initial rate depending on the existent soil moisture content. The rate of infiltration will decrease as the rainfall supply continues and the soil will be less able to take up the water. After some time, the infiltration rate will be reduced to a constant value which is known as the infiltration capacity. The value of the infiltration capacity is mainly dependent on soil type, vegetation and compaction of the ground. This process can be described by an exponential decay (Shaw, 2004). For simplification in the surface runoff model, it is assumed that optimal infiltration is hampered by the sudden high rainfall intensities and compaction of the soil in the urban areas. Therefore, the rate of infiltration is assumed to be at the capacity rate from the beginning of the rainfall event. In addition it is assumed that the groundwater head is continuously below the surface level.

The infiltration parameter is somewhat deviant from the others as it is set up for different land use types with their characteristic infiltration capacities. For the minimum value run, the infiltration capacity is at the minimum range for all the land use types. Analogously, this will be done for the maximum value infiltration capacities. The used infiltration capacities are shown in Table 4-2. The justification of the used values is described in Appendix E .

Table 4-2: Infiltration capacities for different land use types in mm/h.

ID nr.	Land use type	Infiltration capacity minimum	Infiltration capacity default	Infiltration capacity maximum
1	Buildings	0	0	0
2	Water	100	100	100
3	Paved area, paved roads	0	2	6
4	Unpaved roads	0	10	100
5	Unpaved area, nature	100	100	100
6	Remaining, semi-paved	5	10	20

Pit criterion

The creation of the map with local drain directions is dependent on the assigned pit criterion. This condition prescribes the recognition of a pit for a minimum water volume that is needed to fill up a hole in the surface to the overflow level. If the volume of the hole is completely filled with water, the additional surface flow will be drained to another already existing or newly created pit. Initially the model is run with a pit criterion of 10,000 m^3. For the minimum run the parameter will be set on 500 m^3 whereas a value of 20,000 m^3 will be input for the maximum run. The explanation for the relative low value of the minimum run is given by the outcomes of test runs in which the distribution of water at street over the surface seems to be limited in the default situation.

Evaporation

The loss due to evaporation can be considerable at warm surfaces. However, in most cases it is restricted to the evaporation from open water as long as the surface is wet. In Van de Ven (1989), the evaporation calculated for warm asphalt is approximately 1 mm after an hour. Within this period, the surface temperature drops to the ambient temperature. From this evaporation, 50 % takes place in the first 15 minutes as the heat flow is dominating the process. If the surface is warm due to heating of the sun especially in the summer months, the occurring heat flow boosts the evaporation process considerably. Because of the absence of surface temperature measurements, the evaporation during specific rainfall events is hard to quantify.

For the major part of the rainfall events the evaporation is marginal since the surface temperature is supposed to be around the air temperature. Overall, the amount of evaporated water is marginal in comparison with precipitation amounts in heavy events. Therefore the evaporation process is often neglected. Accordingly, the evaporation in both the default and the minimum run is assumed to be zero. The value awarded to the evaporation process in the maximum case will be 1 mm/h with a logarithmic course (see Figure 4-2 below). From time step 360 till 720, the evaporation process will be continued linearly with a rate of 0.4 mm/h. For succeeding time steps, the influence of the evaporation process is small enough to neglect it completely in view of the rainfall intensities and the model input uncertainties.

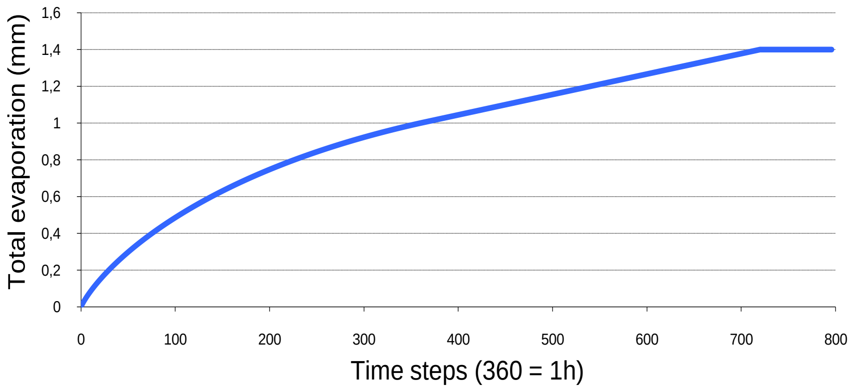


Figure 4-2: The graph shows the total evaporated amount of water during the summer months. After two hours (720 time steps), the evaporation rate is assumed zero which results in the horizontal line in the graph.

4.2.2 Results sensitivity analysis

The results of the model simulations in the sensitivity analysis are compared with the reference (model run number 0) in which all parameters have their default values. The output will be evaluated based on the occurring water at street volume and inundated area. A normative rainfall event with a return period of 2 years and duration of 1 hour has been simulated (18 mm/h).

The results of the sensitivity analysis are represented in the histograms of Figure 4-3. Here, a classification has been made on the basis of both the volume of water and the inundated area in the reference run. All model output is shown quantitatively in Appendix F .

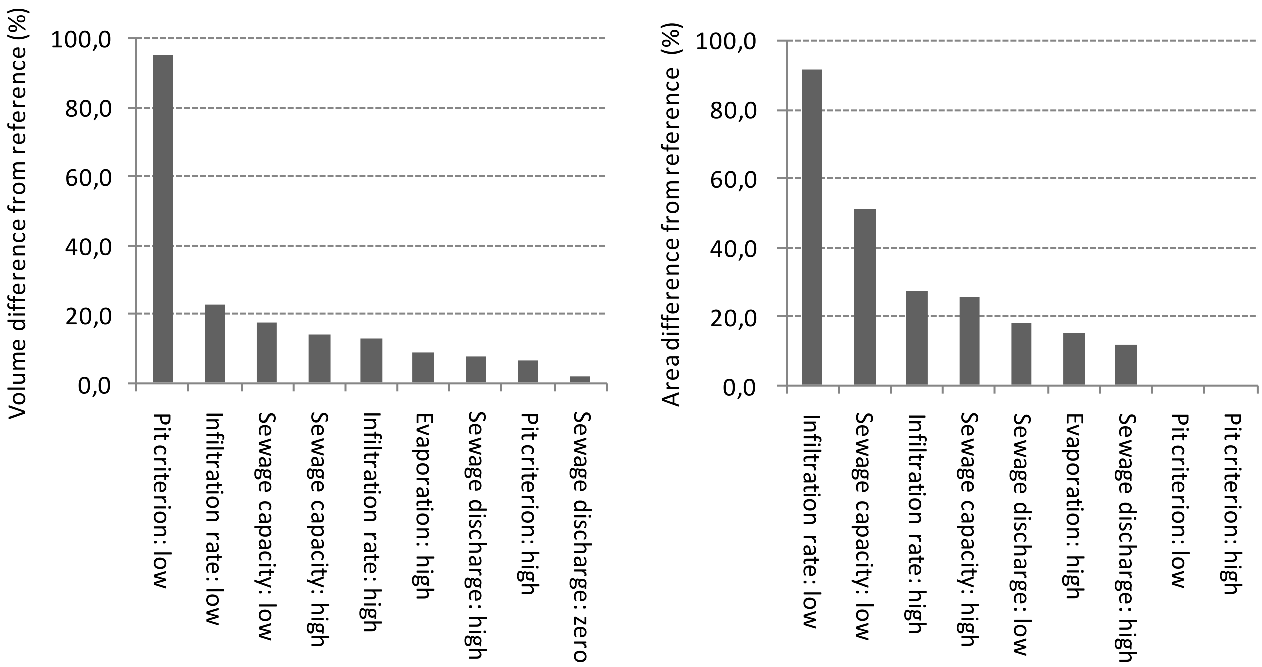


Figure 4-3: Histogram of the sensitivity analysis results, sorted on the basis of the deviation from the total volume of water in the reference run (left) and total inundated area in the reference run (right).

In general, the total volume of water is very divergent for the different model runs while the variations in inundated area are smaller. Model results of some assessed parameters (especially infiltration capacity and sewage storage) turn out to be influential with respect to the water volumes while the inundated areas respond sensitively for especially the pit criterion.

4.2.3 Conclusions sensitivity analysis

Influential parameters

The only parameter that is capable of affecting the inundated area effectively is the pit criterion. Besides, the criterion does not affect the total water volume in the model area. Therefore, the pit criterion can be used for optimization of the water excess distribution.

For calibration of the total water at street volume in the model outcomes, the infiltration rate is the most influential parameter. Therefore, a big effort is allowed to estimate this parameter in the best possible way. Moreover, the sensitivity analysis reveals that measures affecting the infiltration capacities could be interesting to consider. This will be discussed more extensively in chapter 6.

In addition, the initial sewage capacity is of considerable importance. Lowering of the initial capacity is essential in case of surface runoff simulations with already (partly) filled sewage system due to previous events. To aim for more realistic sewage system behaviour, also the implemented measures that affect the storage capacity of the sewage system need to be represented in the model. This leads to locally increased storage capacities. Thus, additional measures, that enlarge the sewage storage capacity, seem to be attractive as well (more extensively discussed in chapter 6). Nevertheless, these kinds of interventions are often unattractive compared to measures above the surface because of the required investment costs and nuisance for the neighbourhood.

Overall, the discharge of the sewage system turned out to be the least important parameter. This may be explained by the relative low discharge rate in comparison to the rainfall intensity. Nevertheless, its effect on the model results cannot be neglected as the absence of flow would increase the volume of water at street by almost 18 %.

Improved model settings

Another outcome of the sensitive analysis is that evaporation will be taken into account for the simulation of the selected rainfall events since its effect cannot be neglected. The total volume of water at street is reduced by 15% in comparison to the reference run if evaporation is implemented, while the inundated area is lowered with 9%. Moreover, the evaporation parameter can be implemented relatively easy in the model.

In the continuation of this study, the default pit criterion will be 500 m^3. The initial pit criterion of 10,000 m^3 will be abandoned as it assigns very high volumes of water to a pit and therefore severely hinders the allocation to larger areas. Additional model runs with a pit criterion below the minimum run (100 m^3) resulted in too many water at street locations. This is unrealistic for the assessed rainfall event (18 mm/h) if it is compared to the area expert information of historical events. Thereby, also the recognition of the most frequent and serious water at street locations, as described in paragraph 2.5, would be complicated.

Limitations and reliability

Initially, some test runs have been executed with a time step of 1 minute. However, the simulated water at street depths in these simulations turned out to be unacceptably high. In spite of the current smaller time step of 10 seconds, still an unrealistic big volume of water was allocated to some of the pits after a time step. This results in inundation depths of several metres in a few pits. Actually, the water excess should be spread more widely over the surrounding raster cells. This has partially been achieved in additional model runs with a lower pit criterion (100 m^3), which resulted in a further increase of inundated area (about 200%). However, the large inundation depths at a few pits still occur. A solution for this problem will probably be found by further reduction of the time step (for example 1 second), but this will lead to an enormous increase in run time of the model which is impractical. For now, the sometimes unrealistic inundation depths are accepted as this is an implication of the model structure with its simplifications. For the purposes of this study, the inaccurate inundation depths and areas are assumed not to hamper the analysis and conclusions too seriously.

The robustness of this sensitivity analysis remains a point of attention. Due to a lack of information concerning the natural or observed variations of the model parameters, model runs with more varying settings have not been done. The results give sufficient information for the following phases in this study as the sensitivity analysis particularly served to get a rough feeling with the parameters and its effects on the model outcomes.

4.3 Model improvements & calibration

In this section, the influential parameters with respect to the water at street volumes are adjusted to optimize the outcomes for specific rainfall events. Hereby, the final parameter values are obtained for application in the modelling of the selected rainfall events. The only available information for the calibration process consists of the identified water inconveniences by the area experts (see Figure 2-7; Lensink & Van ‘t Klooster, 2010).

The sensitivity analysis showed that the infiltration rate is the most important model parameter. Furthermore, the simulation results depend considerably on the sewage storage parameter. Therefore the calibration of the model will be executed by adjustments of these two parameters.

The term calibration seems a bit exaggerated here, as the expert information of the water at street locations and seriousness is mainly qualitative. Inevitably, this affects the reliability of the model results. Therefore, an attempt will be made to estimate the quality of the model outcomes in the discussion (chapter 6).

4.3.1 Framework model improvements & calibration

Since the fine-tuning of the model is an iterative process, some settings in the framework will be dependent on model results in an earlier stage of the calibration.

Two recent events will be used for the calibration, the 4th of August 2010 and the 26th of May 2009. The first rainfall event is not expected to result in appreciable water at street situations according to the area expert information. On the other hand, the event of 2009 is a bit more intense and its simulation should result in some water excess problems at the well known bottlenecks (Figure 2-7). During both events, a period of approximately 15 minutes was observed with high rainfall intensities (see figure Figure 4-4). These periods will mainly contribute to the problems in discharge of storm water.

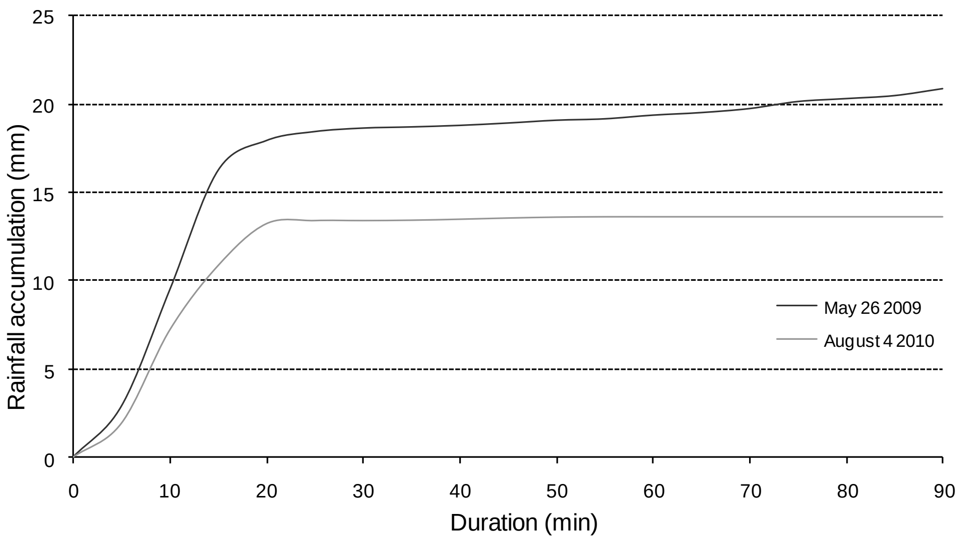


Figure 4-4: Cumulative rainfall depths against time for two historic rainfall events.

The locations that are directive for the judgment of the model performance are (Figure 2-7):

- Stationsplein
- Kersenbaan crossing Utrechtseweg
- Leusderweg crossing Kersenbaan (partially due to rising manhole covers)
- Gerard Doustraat

Improvements by implementation of additional sewage storage

In the past years, some water at street bottlenecks have been solved by means of several measures to the sewage system (see section 2.5.2). These interventions mainly increased the temporary storage in the sewage system and thereby increased the potential water volumes in the sewage system during the event. Implementation of these measures in the model is important for improvement of the model structure and its outcomes. The information of the area experts is guiding for the assessment of the model adjustments.

Due to the location of the additional storage facilities on the edges of "De Berg", they in fact retain the rainfall from the higher situated areas of "De Berg". Therefore, the volumes of water that can be stored in these facilities have to be distributed in the model over the area where the discharges originate from. In this area, the additional storage is converted to millimetres and subsequently added to the default storage capacity of 7 mm. The consequence is that the additional storage capacities in for example the Kersenbaan and the Vondellaan / van Campenstraat need to be modelled differently in comparison to the real situation which would require an extensive sewage system model.

Implementation of the additional sewage storage should not hamper the occurrence of water at street at the well known locations. Therefore an analysis has been done for some different scenarios of the various storage parameters. Besides the run with full attendance of the implemented storage facilities, also runs with half of the capacity and without additional storage have been simulated. This way, the impact of the additional storage implementation on the model outcomes can be assessed. An overview of the model runs regarding the additional storage can be seen in Table 4-3 below.

Table 4-3: Values of the additional storage (m^3) in different runs for model improvement.

	Run 1, 4*	Run 2, 5	Run 3, 6
Kersenbaan	1,000	500	0
Infiltration van Campenstraat	1,620	810	0
Leusderweg	1,200	600	0

* Runs 1 through 3 simulate the event of August 4 2010 while runs 4 – 6 assess May 26 2009.

Calibration by infiltration rate adjustments

In addition to the implementation of additional storage facilities, more realistic model results may be attained by adjustment of the infiltration parameter. With respect to the initial infiltration rate values, some variations will be made. Especially the increase of the infiltration parameter will be emphasized since the water at street volume is assumed to be overestimated in the model runs of the sensitivity analysis.

Table 4-4: Applied infiltration rates (mm/h) for the different calibration runs.

	Land use type	Infiltration rates				
		Initial	Decreased	Increased	Increased II	Increased III
1	Buildings	0	0	0	2	2
2	Water	100	100	100	100	100
3	Paved area, paved roads	2	1	4	5	6
4	Unpaved roads	10	7.5	12.5	12.5	15
5	Unpaved area, nature	100	100	100	100	100
6	Remaining semi-paved	10	7.5	12.5	12.5	15

The unpaved surfaces of category 5 will be treated as fully permeable. Therefore an (unrealistic) high rate of 100 mm/h is awarded to prevent surface runoff from this land type. However, in reality the saturation of unpaved surfaces will reduce the infiltration capacities of the soils. Due to a lack of information from infiltration rates in the urban area as well as the response of different urban land use types to heavy rainfall, it is uncertain whether surface runoff from unpaved areas may be expected. In this study it is assumed, also by reason of the sandy soils in Amersfoort (De Bosatlas van Nederland, 2007), that the rainfall intensity is smaller than the infiltration capacity of the unpaved areas. The infiltration rate is therefore equated with 100 mm/h for all calibration runs.

In the model calibration runs with the increased infiltration rates (increased II and increased III), the value of the infiltration on paved surfaces is increased. Further increase of this parameter seems unrealistic, but is implemented to account for initial losses (retention on the surface) and interception. The initial loss partly consists of the moistening loss, the water amount absorbed on the paved surface that can only disappear by evaporation. This is already integrated in the evaporation parameter. Besides the initial loss is particularly due to the forming of puddles, which remain on the paved surfaces as a result of local terrain variations. These aspects will not contribute to sewage inflow, nor to surface runoff. For the initial loss a value of 0.5 mm is assumed according to the experimental experiences by Van de Ven (1989). Furthermore, interception of rainfall by for example vegetation will reduce accumulation on the surface. Also the surface storage on flat roofs restricts the drainage to the sewage system. The mentioned processes have been taken into consideration by adopting a value of 2 mm for the built-on area. The processes described above, are suitable to integrate in the infiltration as this parameter actually prescribes the water amount that will not reach the surface or will not result in surface runoff.

4.3.2 Results model improvements & calibration

The outcomes of the model improvement and calibration runs are compared in a qualitative manner as the information of water at street is of insufficient accuracy for quantitative comparisons. Therefore, the inundation maps will be used since they show the occurrence of water at street and locations with the most serious problems. The comparison of the inundation maps is described below.

Improvements by implementation of additional sewage storage

For the event of August 4 2010, negligible differences could be observed between the model runs with the varied additional storage capacities as in Table 4-3. Overall, negligible water at street has been generated for the model area. Moreover, little water at street has been simulated for most part of the identified locations. This situation corresponds well with the expected water excess extent.

From the model runs of the rainfall event of 26th of May 2009, it appeared that with the full implementation of the storage facilities still water at street occurs on all of the recognized bottlenecks. Therefore the effect of increased infiltration rates are assessed on the basis additional storage volumes of model runs 1 and 4 in Table 4-3.

Calibration by infiltration rate adjustments

The occurrence of water at street during the various simulation runs with its specific infiltration settings are shown in Table 4-5. The results will be further explained hereafter.

Table 4-5: Occurrence of water at street for the different calibration runs.

Infiltration settings	Simulated water at street	
	May 26 2009	August 4 2010
Decreased	Yes	Yes
Initial	Yes	Yes
Increased	Yes	Yes
Increased II	Yes	No
Increased III	No	No
Expected outcome	**Yes**	**No**

The calibration runs with increased infiltration parameters still show too much water at street for the event of August 4 2010. A part of the model area is depicted in Figure 4-5 (left) in which the occurrence of water at street can be noticed clearly. The effect of the increased II infiltration parameter is displayed in the map on the right side of Figure 4-5. Here, the appearance of frequent water at street locations is negligible. Still a few small blue spots can be noticed on the inundation map, but these can be characterized as puddles. Further examination of a few larger blue areas has shown that they can mainly be attributed to inaccuracies in the model elevation (AHN 1) and land use map.

Application of parameter values according "Increased II" for the event of the 26th of May 2009 still causes the appearance of inundated areas. Thus, these model settings seem to come closest to the real situation. This statement is supported by the analysis of the model run with even higher infiltration capacities (III). The results for these parameter values with respect to the rainfall event of August 4 2010 are satisfying. However, the higher infiltration rates also prevent the occurrence of water at street in the event of May 26 2009, which results in undesired model responses.

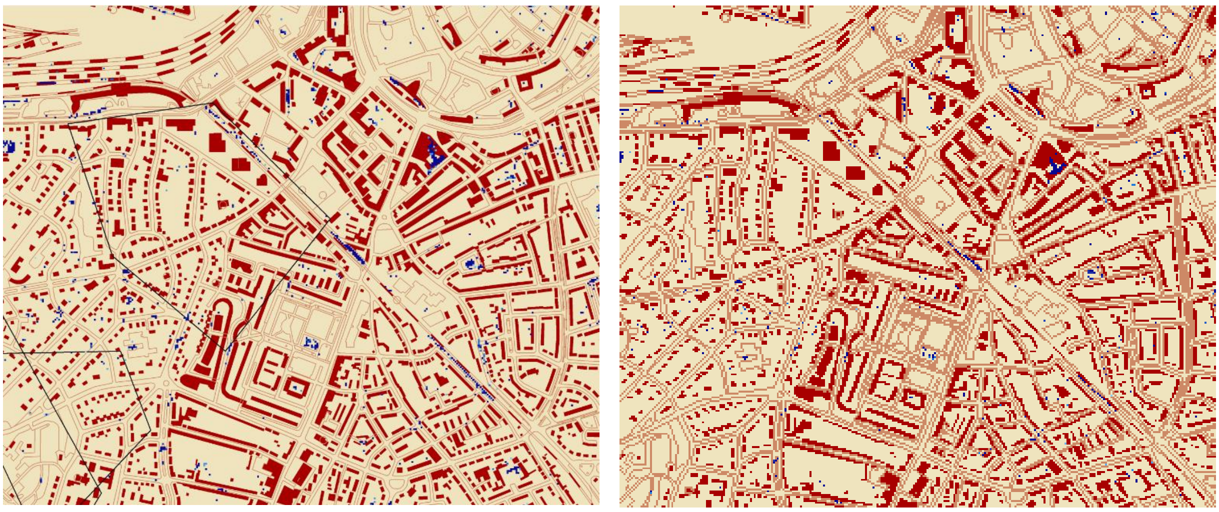


Figure 4-5: Left: the inundation map for increased infiltration parameters still shows water at street (in blue) for the rainfall event of August 4, 2010. Right: the further increased infiltration parameters result in little water at street situations.

4.3.3 Conclusions model improvements and calibration

After execution of the model calibration, the final infiltration parameter values for the model simulations have been acquired. These values are presented in Table 4-6. For completeness, the values of other model parameters that have been defined during this chapter are depicted in Table 4-7.

Table 4-6: Final values of the infiltration parameters.

Land use type	infiltration rates (mm/h)
Buildings	2
Water	100
Paved roads	5
Unpaved roads	12.5
Nature / green	100
Remaining semi-paved	12.5

Table 4-7: Parameter values for the simulation of selected rainfall events

Parameter	Final simulation values
Sewage storage capacity	7 mm *
Sewage discharge capacity	0.7 mm/h
Pit criterion	500 m3
Evaporation	1.4 mm **

* Higher values in areas with additional storage facilities.

** 1 mm evaporation occurs in the first hour and 0.4 mm in the second hour (according a logarithmic course).

It should be mentioned that the values above provide acceptable model outcomes given the available and restricted information of historical events and the infiltration processes in the urban area. Therefore, more extensive model calibration may reveal other combinations of the parameter values which result in similar outcomes. However, the acquired values are assumed to be suitable for the purposes of this study.

Besides, the measures to the sewage system like additional storage and infiltration facilities have successfully been implemented. The outcomes proved that on several locations, as mentioned by the area experts, the water at street problems have decreased significantly. Some locations even do not show water excess problems at all after the implementation of the measures.

Next, it turned out that the achievement of a modelled situation without any water at street for the assessed event would require even much higher infiltration rates. However, a little water at street in the inundation map is tolerated. This is unavoidable since the maps also show small water at street spots or puddles, which would not be recognized as water at street. Consequently, these spots are unimportant for the assessment of water inconvenience and possible damages.

5 RESULTS MODEL SIMULATIONS

After the model processing in chapter 4, the rainfall-runoff model could be applied for the simulation of the selected rainfall events. In this chapter, the output of these model simulations is explained. First the generated model output for the various input sources is evaluated. Hereafter a qualitative analysis is described in case of meaningful differences or remarkable model output by means of the generated inundation maps. Subsequently, the differences between radar, spatially averaged radar and rain gauge results are compared with each other in a more quantitative way based on obtained water at street volumes. With the help of this chapter, the research questions with respect to the model simulation outcomes will be answered:

2. *Is the spatial distribution in the identified events meaningful for the simulation of water at street in comparison to a spatially averaged rainfall depth for the whole study area?*
3. *What are the effects of the use of radar rainfall information with its higher spatial resolution on the simulated water accumulations in the study area in comparison to the results based on rain gauges?*
4. *What is the dependency of the model results on the specific properties of extreme rainfall events and influencing areal characteristics?*

5.1 Evaluation of water at street simulations

The surface area of water at street is evaluated in a qualitative analysis of the inundation maps. Quantitative analysis of the inundation areas would often be misleading as higher water excess volumes partly appear as higher inundation depths instead of increased inundated areas. This shortcoming of the model requires the assessment of the water at street volumes for a quantitative comparison of the model output. Explanations of the different model results may first of all be found by consideration of the differences in rainfall input information.

5.1.1 Generated model output

Since the rainfall events have been selected on the basis of the weather radar data, the selection criteria are not satisfied for all of the spatially averaged radar and rain gauge data. Therefore, all rainfall events are supposed to result in water excess for the simulations of the spatially variable radar data while they may not always show water at street for the other rainfall input sources. In Table 5-1 an overview is given of the cumulative rainfall depths and the water at street occurrence in the model runs of spatially averaged radar and rain gauge data.

Table 5-1: The occurence of water at street for rainfall input of spatially averaged radar and rain gauge.

Rainfall event	Spatially averaged radar (mm)	Water excess?	Rain gauge (mm)	Water excess?	Rainfall depth difference
June 15, 1998	7.8	No	9.0	No	15.4%
July 29, 2000	14.7	No	43.1	Yes	193.2%
August 7, 2001	22.1	Yes	12.7	No	-42.5%
July 28, 2006	29.8	Yes	0.0	No	-100.0%
July 5, 2007	27.3	Yes	16.4	No	-39.9%
June 3, 2008	21.4	Yes	16.6	Yes	-22.4%
September 12, 2008	24.0	Yes	42.2	Yes	75.8%
May 26, 2009	16.0	Yes	18.4	Yes	15.0%
August 28, 2009	23.1	Yes	23.2	Yes	0.4%
July 10, 2010	37.8	Yes	35.5	Yes	-6.1%
August 4, 2010	11.6	Yes	9.0	Yes	-22.4%
August 26, 2010	40.5	Yes	67.8	Yes	67.4%

In comparison to the rainfall depths in the rainfall accumulation maps of Appendix D , the values in Table 5-1 are composed of both the selected event (see chapter 3) and the preceding rainfall. The latter determines the initial filling up of the sewage system. Besides, in some cases also some continuation of rainfall after the selected duration has been taken into account to simulate the complete event in the most truthful way.

Next to the rainfall depths itself, the rainfall intensities during the event seem to be of major importance for the generation of water excess. This is confirmed by the comparison of two rain gauge events with rainfall depths of 9 mm for which only one resulted in water at street. Based on this relative low rainfall depth, no water excess at all is expected.

The right column in Table 5-1 shows the differences between the rainfall depths of rain gauge and spatially averaged radar in terms of percentages. How these different rainfall inputs affect the model simulations is explained in the following paragraphs. Given the absence of water at street situations in several model runs, some comparisons cannot be made. However the absence of water excess in particular model runs is already an important aspect for discussion.

5.2 Comparison of inundation maps

First of all, the comparison of the inundation maps in case of perceptible or remarkable differences regarding the inundated areas will be discussed. Inundation maps for all other model runs are included in appendix G . The maps are used to assess the impact of different rainfall input sources qualitatively. Moreover, it provides a clear view of possible bottlenecks in the urban drainage system. The locations as identified by the area experts (paragraph 2.5) are used for the identification of locations with the serious water excess in the various model runs.

In general the visible differences between the simulation runs of spatially variable and spatially averaged radar input are small and will therefore particularly be mentioned during the quantitative analysis in the next paragraph.

July 29, 2000

According to the radar rainfall accumulation map of July 29, 2000 (see Appendix D), the heaviest rainfall took place at the south-western part of Amersfoort, mostly outside the model area and in the vicinity of rain gauge station Soesterberg. This KNMI rain gauge recorded a rainfall depth of 43.1 mm in 1 hour which is very extreme (1 / 100 yr). On the other hand, the maximum observed rainfall depth of the weather radar in the study area was 24.3 mm. Based on the high degree of spatial variability in the rainfall accumulation map of the radar, it is likely that the most extreme part of the rainfall event occurred very locally. By taking the value of Soesterberg for the model area, the rainfall depth and thus water excess has probably been overestimated seriously (see Figure 5-1). This has resulted in 17 times more water excess in the rain gauge run compared to the radar run. On the other hand, the weather radar could have underestimated the rainfall in case of high rainfall intensities and with it appearing observation errors (Overeem, 2009). Due to a lack of information concerning historical water at street situations, a judgment of the most reliable model output is very difficult. Nevertheless, the picture emphasises the possible effect of spatial variability and the use of data that has been recorded outside the area of interest.

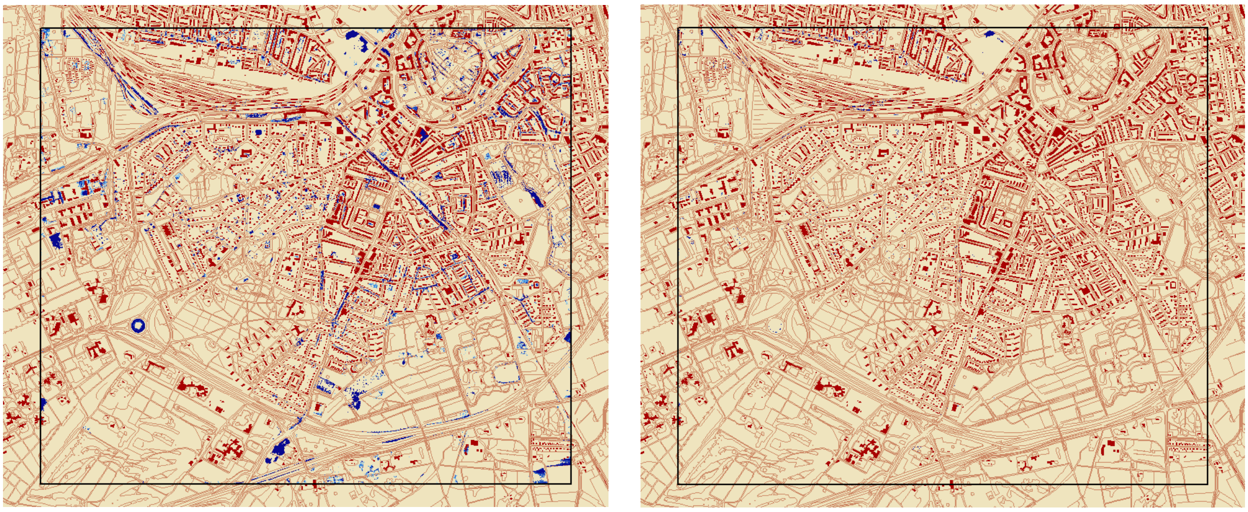


Figure 5-1: The simulated water at street situations (blue areas) for the rainfall event of July 29, 2000 with input of rain gauge data (left) and input of spatially distributed radar data (right).

July 28, 2006

By the information of both area experts and the municipal sewage plan (Amersfoort, 2008), this event is appointed as one that caused serious water inconveniences in the urban area of Amersfoort. However, the event could only be simulated with the radar data as KNMI station Soesterberg measured no rainfall at all on the 28th of July. This contrast between the rainfall data sources seems to be unlikely, but is confirmed by the picture of the rainfall variability in the surroundings of Amersfoort (Appendix D). For this case it is clear that the effect of the extreme rainfall in the study area could not be represented by the measurements of the rain gauge station.

June 3, 2008

The differences between the inundated area of the spatially variable and spatially averaged radar input are less than 2 %. Nevertheless, the model output of the rain gauge data shows about a half of the inundated area with respect to the radar input sources. See figure Figure 5-2 below. This has been caused by the lower rainfall depth at the rain gauge station in comparison to that in the model area. During a period of in total 3 hours, KNMI station Soesterberg observed an amount of 16.6 mm which corresponds well with the overlapping radar pixel. However, according to the radar data an additional rainfall amount of more than 4 mm has been simulated on average for the model area. The explanation of the impact of just a few millimetres of rainfall is given by the fact that all the additional rainfall contributed to the surface runoff whereas the rain gauge amount just resulted in water at street.

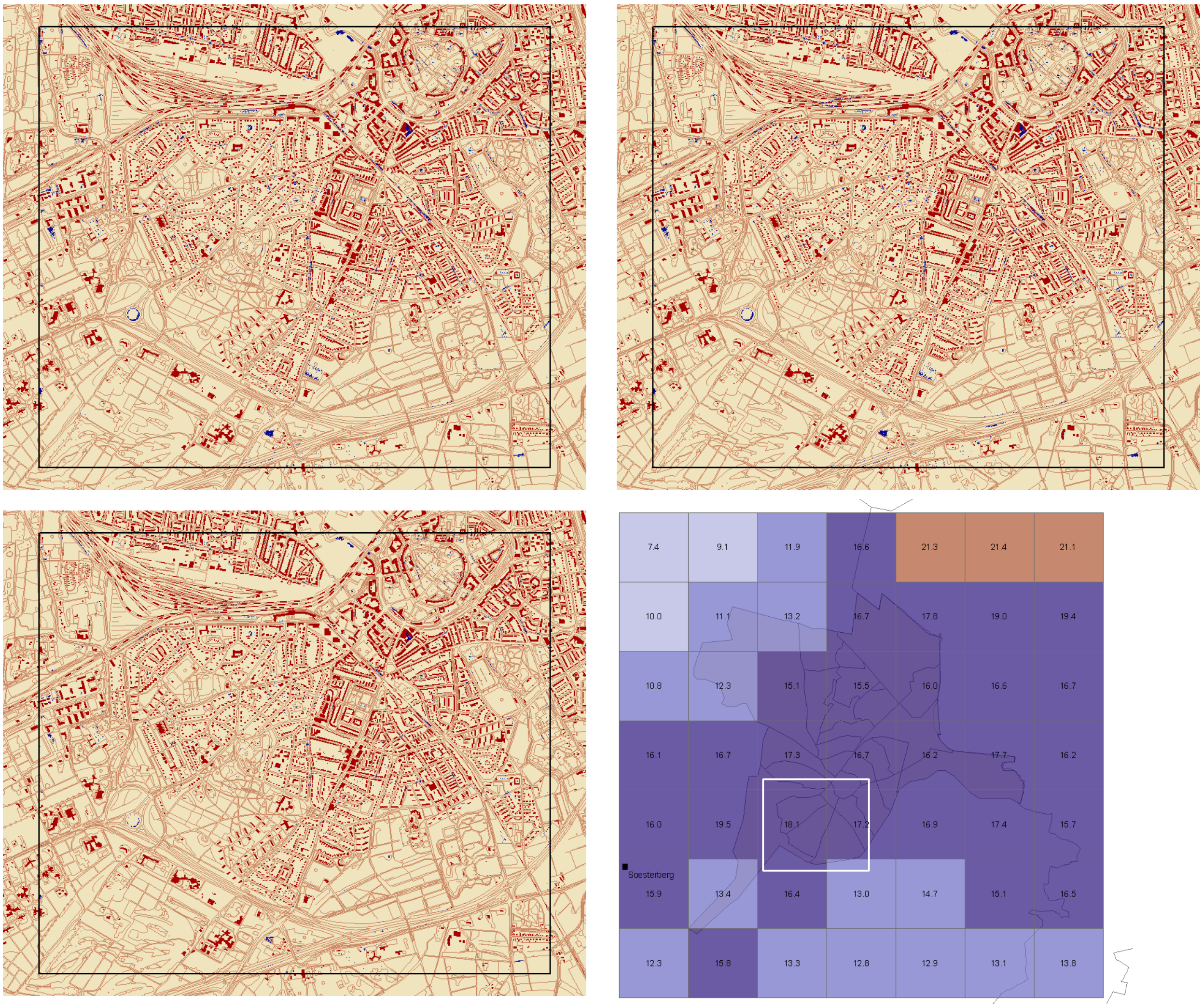


Figure 5-2: The model results of the rainfall event of June 3, 2008 (bottom right). The generated water at street locations have been shown for the input of variable radar (top left), spatially averaged radar (top right) and the rain gauge (bottom left).

September 12, 2008

This rainfall event shows a similar picture as the event of the 29th of July 2000. Again the measured rainfall depth at the rain gauge station is much higher than the radar input for the model area. Therefore the inundation map of the rain gauge input shows extreme water at street situations whereas the two maps of the radar input show little water excess. Most of the differences appear in the first hour of the rainfall event in which rain gauge station Soesterberg recorded an amount of 29 mm. In the same time span the maximum value observed by the weather radar was about 16 mm for the model area. The effect of the big input differences have been translated in eight times bigger water at street surfaces for the rain gauge results.

The area experts did not mention this rainfall event as one with serious water at street problems. The lack of information concerning historical water inconveniences prevents the evaluation of the most reliable outcomes.

May 26, 2009

Since 2009, the differences between the spatially variable and spatially averaged radar may show up clearer in the inundation maps as a result of the increased spatial resolution of the radar data. The comparison between the results of the radar input sources (see Figure 5-3) for the event on the 26th of May 2009 reflects the high spatial variability in the rainfall data. Although the visible differences are not very clear, important urban districts show deviations. Especially in the areas just south of the town centre with most of the identified bottlenecks, more severe water at street situation has been generated in case of the spatially variable radar input. This is caused by local high rainfall depths (see rainfall map in Appendix D). On the other hand, for some locations in the north-western part of the model area less or no water excess has been simulated. This reveals that the water volume is distributed more equally over the model area in the model runs of the spatially averaged radar. Consequently, some problems that were noticed in reality may not be simulated.

Additionally, the inundation map of the rain gauge input can be found in appendix G . Here, the water at street situation is more serious because of the rainfall measurement in the area with the locally highest rainfall depths.

Figure 5-3: Inundation maps of the spatially variable (left) and spatially averaged radar (right) input for the rainfall event of the 26th of May 2009.

August 28, 2009

The simulated inundated area in case of the spatially variable and spatially averaged radar input are corresponding due to the more uniform rainfall pattern in most of the model area. Based on the nearly equal rainfall depth at the rain gauge station, comparable results are also expected for the water at street surface. However, a larger inundated area can be seen clearly and turns out to be approximately 25% more than for the radar data input. The explanation for these outcomes is the variation in rainfall intensities during the event. The increased temporal resolution of the rainfall observations for both radar and rain gauge, 5 minutes instead of 1 hour as before 2009, enabled more detailed measurements. Based on the rain gauge data, it appeared that the rainfall intensities are larger and that the total rainfall time is smaller. In this case, the infiltration surplus is significantly larger and thereby also the water excess.

July 10, 2010

In comparison to the previous rainfall event of August 28 2009, similar results have been acquired with the model simulations of the 10th of July 2010. Also for this event, the rainfall depths of the various rainfall data sources are close to each other (37.8 mm versus 35.5 mm, see Table 5-1). However, again the output of the model run with the rain gauge input shows much more water at street while the rainfall depth is even about 6% smaller than for the spatially averaged radar. The course of the rainfall event according to the spatially averaged radar and the rain gauge data may explain the simulation differences (see Figure 5-4). Despite the almost equal total rainfall depths, the rainfall measured by the rain gauge shows longer lasting periods with high intensities. A total amount of approximately 33 mm is measured during the periods with high intensities for the rain gauge in comparison to 27 mm for the spatially averaged radar. So, according to the radar observations the rainfall is spread more over the total event time. For the rain gauge simulation, this results in less ability to drain into the sewage or infiltrate in the permeable surfaces.

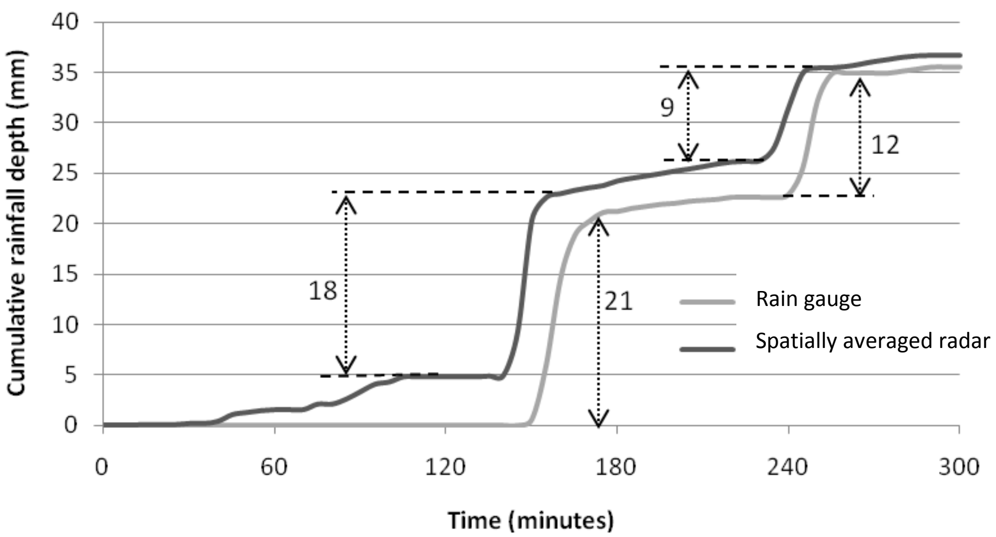


Figure 5-4: The course of the rainfall event on July 10 2010 plotted against the time for the spatially averaged radar input and the rain gauge input.

August 26, 2010

The difference between the measured rainfall depths of the weather radar and the rain gauge station is enormous for the rainfall on August 26 2010. This event has been characterised by long-lasting rainfall over the day with a few periods of intensive rainfall. In Figure 5-5 the cumulative rainfall is depicted to show the development of the deviations in the rainfall sources. The difference is about 27 mm or 67%. Obviously, this will have a major impact for the simulated water at street situations.

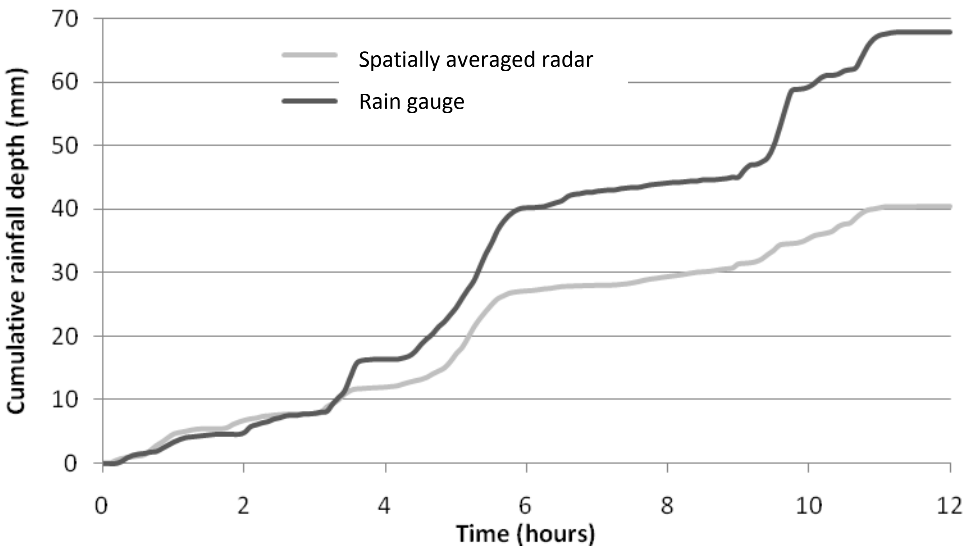


Figure 5-5: The course of the rainfall event on August 26 2010 plotted against the time for the spatially averaged radar input and the rain gauge input.

The inundated area of the rain gauge model run is about twice the size of the radar runs, which indicates the enhancement of rainfall input differences in the water excess generation. The spatially averaged radar run differs visually only a bit with respect to the distribution of the water at street situations in the spatially variable radar. The rainwater volume, which is equal by definition, has been distributed differently. This caused lower rainfall depths in the southern part and higher rainfall depths in the northern part of the model area in case of the spatially variable radar. In appendix G , the inundation maps can be seen in which serious water at street situations have been simulated. However, according to area experts the rainfall event only led to limited water inconveniences. Therefore the model simulations are doubtful and are expected to overestimate the degree of water at street. This is caused by the restrictions of the model in which the water at street, once simulated, cannot be drained anymore. Even in situations in which a dry period or drizzle takes place, for example between the sixth and ninth hour in Figure 5-5. Nevertheless, the model results can still be used to assess the effect of spatial variability in the outcomes as well as the difference between the homogenous radar and rain gauge results. For this purpose, the simulated water excess has to be considered as the total or summed water at street that occurred during the whole event. In this case, it could only be concluded that the application of rain gauge data instead of radar data creates more serious water at street.

5.3 Comparison of water at street volumes

In this paragraph a more quantitative analysis is performed with the model results of spatially variable radar, spatially averaged radar and rain gauge data. To this end, the total water volume in the model area has been calculated on the basis of the water depth in the inundated cells and the number of inundated cells after the final time step. Below, the output of the rainfall data sources will be assessed according to the comparison method presented in section 3.2.

5.3.1 Comparison spatially averaged radar versus spatially variable radar

In order to assess the effect of spatial variability in the rainfall input on the simulated water at street situations, the model output of the spatially averaged and the spatially variable radar are compared. In Table 5-2 below, the results in terms of water at street volume are depicted. The absolute volumes are not evaluated as the model accuracy is assumed to be insufficient for such an analysis. According to the study objective, more attention is given to the relative differences between the various simulations. Therefore, an overview is given of the differences between the simulation output of spatially variable and spatially averaged radar. Furthermore, the coefficient of variation is used as an indicator for the degree of spatial variability in the rainfall accumulation map of the radar. High values of this coefficient correspond to a high spatial variability in the rainfall event (see paragraph 3.1.2). In consequence of the increased spatial resolution of the radar since 2009, the outcomes before this time cannot be compared with the ones in the recent years.

Table 5-2: Comparison of model results for spatially variable and spatially averaged radar data.

Rainfall event	Simulated water at street volume (m^3) Radar spatially averaged	(m^3) Radar spatially variable	Difference (%)	Spatial variability (C_v in %)
June 15, 1998	0	685	-	85.8
July 29, 2000	0	1,245	-	65.0
August 7, 2001	8,651	10,039	16%	32.8
July 28, 2006	16,327	18,007	10%	13.5
July 5, 2007	4,670	4,071	-13%	16.2
June 3, 2008	10,211	10,406	2%	10.9
September 12, 2008	2,618	2,396	-8%	12.8
May 26, 2009	11,900	19,512	64%	27.1
August 28, 2009	10,625	11,461	8%	7.1
July 10, 2010	71,974	67,887	-6%	15.9
August 4, 2010	4,180	8,345	100%	16.4
August 26, 2010	20,792	23,753	14%	8.9

Despite the equal rainfall volume in the model area for the spatially averaged and spatially variable radar input, the simulated water excess varies considerably in some of the model runs. This can for instance be seen in the absence of simulated water at street in the spatially averaged radar runs of the events in 1998 and 2000. Here, the locally high rainfall intensities have been averaged out too much in the rainfall depth value for the whole study area.

Moreover, Table 5-2 shows that the possibility to represent the spatial variability in the study area for the period 1998-2008 is smaller than for the more recent rainfall events due to the restricted spatial resolutions. This seems to be visible in the table where the differences before 2009 are up to 16 percent at maximum against 100 percent after 2009. For the higher resolution radar data since 2009, two runs exist with vast differences between the two radar input sources. The first rainfall event, the 26th of May 2009, has locally high rainfall depths in the sensitive areas just south of the city centre. The lowest rainfall depths took place in the south-eastern part of the model area that is not very sensitive to water at street, even in case of increased rainfall depths with the spatially averaged radar input. The explanation for the restricted water excess in the south-eastern part is given by the high degree of unpaved, natural grounds.

The other striking rainfall event of the 4th of August 2010 shows a round difference of 100%. This remarkable model result has probably been caused by the very little water excess in the event. Next to this, the water at street has only been generated in a few radar pixels for the spatially variable radar. As the maximum rainfall depths have been flattened out for the spatially averaged radar input, negligible water at street remains. Although the difference is 100%, the water excess in absolute values is not significant for both model runs.

The results are visualised in Figure 5-6 in order to investigate possible coherence between the spatial variability of the rainfall and the simulated water at street differences. No clear relationship can be found in the graph. The only notable outcome is that most of the rainfall events are clustered in the region with absolute differences below 20% and a coefficient of variation between 7 and 17. Three data points are separated from this cluster. If the rainfall event of

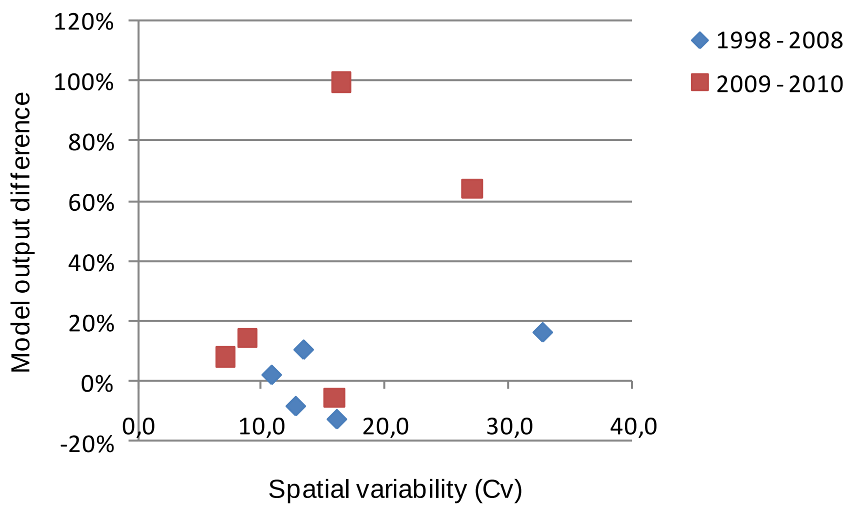


Figure 5-6: Model output difference between spatially averaged and spatially variable radar information as a function of the spatial variability, which is represented by the coefficient of variation (Cv).

August 4 2010 (difference of 100%) is left aside, the two highest values of the spatial variability have occurred in conjunction with the two highest model output differences. The main explanation for these variations is the occurrence of locally high rainfall depths in the spatially variable radar input, which seem to dominate in the generation of water at street. In spite of the restricted number of data points, the graph may indicate a dependency of the model output differences on the spatial variability of the rainfall for the two radar data sources. Additional radar rainfall information of future events is required to support this statement.

5.3.2 Comparison spatially averaged radar versus rain gauge

The secondly assessed comparison is the one between spatially averaged radar and rain gauge output. This analysis reveals the effect of spatially averaged radar data use in which information of all radar pixels in the model area have been incorporated, in comparison to the rain gauge information. The latter is based on the input of one measurement location outside the model area before 2009 and in the central part of the model area since 2009 (paragraph 2.3). The outcomes of the model simulations (see Table 5-3) show much more differences with respect to the water at street volume compared to the previous comparison between the two radar input sources. Several of the rain gauge observations at KNMI station Soesterberg have not even recorded sufficient rainfall to cause a water at street situation. In the remaining model runs, the differences vary widely with the most remarkable outcome for the rainfall event on the 12th of September 2008. From the rainfall map it turns out that the heaviest part of the rainfall event occurred southwest of Amersfoort where the rain gauge station was situated. The almost double rainfall depth at the rain gauge station has caused almost 25 times more water at street volume in the model area.

Table 5-3: Comparison of model results for spatially averaged radar and rain gauge data.

Rainfall event	Simulated water at street volume (m^3) Radar spatially averaged	(m^3) Rain gauge	Difference with respect to radar (%)	Spatial variability (C_v in %)
June 15, 1998	0	0	-	85.8
July 29, 2000	0	86081	-	65.0
August 7, 2001	8,651	0	-	32.8
July 28, 2006	16,327	0	-	13.5
July 5, 2007	4,670	0	-	16.2
June 3, 2008	10,211	4,054	-60%	10.9
September 12, 2008	2,618	64,892	2,378%	12.8
May 26, 2009	11,900	30,771	159%	27.1
August 28, 2009	10,625	15,553	46%	7.1
July 10, 2010	71,974	93,844	30%	15.9
August 4, 2010	4,180	47	-99%	16.4
August 26, 2010	20,792	74,874	260%	8.9

In general, the tendency is that differences in input rainfall depth are enhanced in the water at street extent of the model simulations. The addition of a few millimetres of rain is important as this amount often fully contributes to the surface runoff and therefore to the water at street volume. This emphasises the importance of accurate and reliable rainfall measurements in addition to good model behaviour.

A high spatial variability of the rainfall event has not resulted in higher differences between the rain gauge and spatially averaged radar outcomes. This implies that the rainfall events with the lowest spatial variability values do not automatically show the smallest differences between the rainfall input sources. Therefore, it appears that the simulation differences for this comparison cannot be explained by the spatial variability. Other factors have more influence on the model outcomes than the spatial variability. As described before in paragraph 5.2, model output variations can also be clarified by differences in total rainwater volume, measured rainfall duration and rainfall intensity. From the graph in Figure 5-7, it turned out that the rainwater volume in the model area indeed affected the model output to a great extent. In this graph, the model output differences in terms of percentages are plotted against the rainfall input differences in the event. Except from the deviant and extreme data point of the 12th of September 2008, the data points are positioned rather in line. The value of the model output difference increases for increasing differences in the rainfall input. From the graph, it becomes clear once more that the differences in rainfall input are enhanced in the model executions in terms of water at street volume.

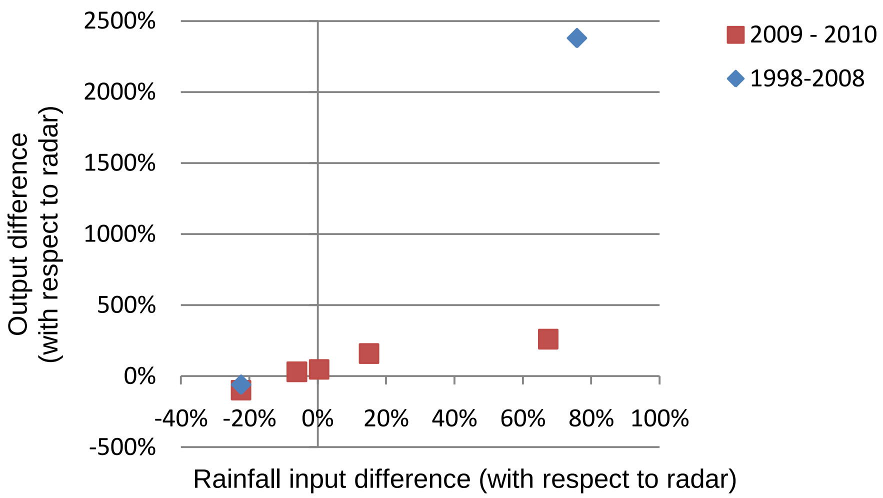


Figure 5-7: Model output difference between spatially averaged radar and rain gauge information as a function of the difference between the rainfall input in the model area.

5.3.3 Comparison spatially variable radar versus rain gauge

The last comparison is the one between the spatially variable radar and rain gauge model results. Unlike the previous comparison, the input of the radar now has its original spatial resolution of 1 or 2.5 km. The results are represented in Table 5-4 in which the differences are sometimes enormous. Broadly speaking, these percentages are comparable to those of Table 5-3. However, in addition a comparison of the rainfall event on the 29th of July 2000 could be made. This rainfall event shows the most extreme difference between the radar and rain gauge outcomes. This can be explained by the occurrence of just a bit of water at street in case of the radar input whereas the rain gauge measured very high rainfall depths with accompanying consequences for the water excess. The spatially variable rainfall pattern of the event is the most important source for the variations in the two rainfall input files (see also paragraph 5.2).

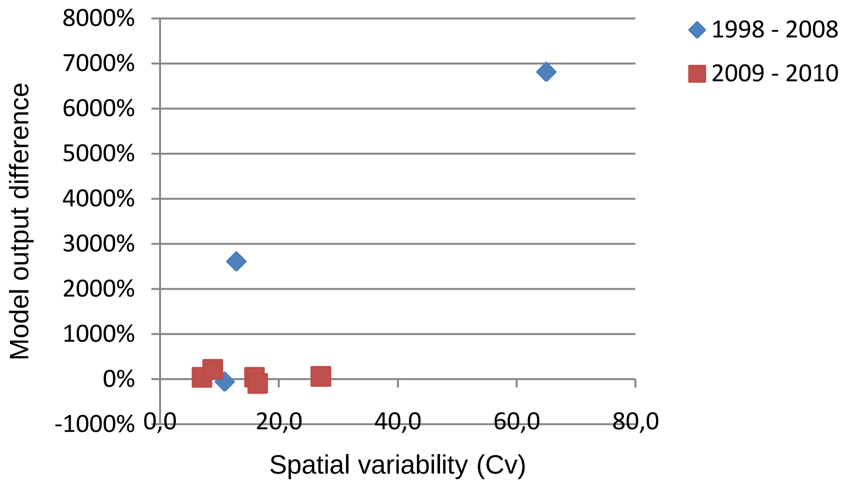
Table 5-4: Comparison of model results for spatially variable radar and rain gauge data.

Rainfall event	Simulated water at street volume (m^3) Radar spatially variable	(m^3) Rain gauge	Difference (%)	Spatial variability (C_v in %)
June 15, 1998	685	0	-	85.8
July 29, 2000	1,245	86,081	6,813%	65.0
August 7, 2001	10,039	0	-	32.8
July 28, 2006	18,007	0	-	13.5
July 5, 2007	4,071	0	-	16.2
June 3, 2008	10,406	4,054	-61%	10.9
September 12, 2008	2,396	64,892	2,608%	12.8
May 26, 2009	19,512	30,771	58%	27.1
August 28, 2009	11,461	15,553	36%	7.1
July 10, 2010	67,887	93,844	38%	15.9
August 4, 2010	8,345	47	-99%	16.4
August 26, 2010	23,753	74,874	215%	8.9

In four rainfall events no water at street has been simulated with the rain gauge input. Among these events is the one with the highest value for the coefficient of variation in which insufficient rainfall was measured at the location of the rain gauge for the appearance of surface runoff. Also for the other three events, the location of rain gauge station Soesterberg has major impacts on the observed rainfall depths. Therefore, a measurement location outside the model area frequently appeared to be inappropriate for the representation of heavy rainfall within the model area. Nevertheless, the rainfall event of August 28 2009 shows a quite uniform rainfall pattern, which resulted in almost equal rainfall depths for the spatially variable radar and the rain gauge runs. Although the smallest differences have been generated for this event, still a deviation of 36% exists between the rain gauge and spatially variable radar runs. Also in this case, the differences originate from factors like the rainfall intensities.

Again a graph is presented in which the effect of the spatial variability on the differences is visualised (see Figure 5-8). It is notable that the most serious differences between radar and rain gauge have taken place for the rainfall events before 2009. This demonstrates the fact that the rainfall has been measured outside the model area in contrast to the events since 2009. However, still significant differences exist for the latter events.

If the data points with the two highest differences are omitted (bottom graph in Figure 5-8), a better picture of the events in the period 2009-2010 can be obtained. It turns out that the data points are scattered without any trend or relationship. The only remarkable observation is that the smallest output difference occurs for the most uniform rainfall event and the largest difference in case of the most spatially variable event. As this only comprises two single points on the graph, decisive conclusions cannot be drawn.



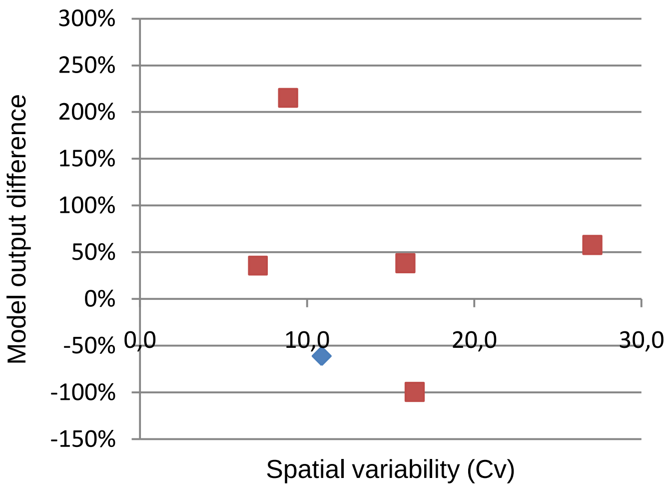


Figure 5-8: Model output difference between spatially variable radar and rain gauge information as a function of the spatial variability, which is represented by the coefficient of variation (Cv). The bottom graph is a zoomed in part for the events of the period 2009-2010.

5.4 Conclusions model results

Based on the three comparisons described above and the analysis of inundation maps, it can be concluded that the rainfall measurement location is responsible for considerable variations in rainfall input and modelled water excess. Especially in the period 1998-2008, the effect of the rain gauge location outside the model area is prevailing over other factors. This statement is supported by four out of six events that provided insufficient rainfall in the rain gauge runs for the generation of surface runoff. In view of the spatial distribution in the radar rainfall data, it often seems to be inappropriate to use information of extreme rainfall events from a gauge situated some kilometres outside the model area. Since 2009, the effect of spatial variability in smaller spatial scales plays a more important role as a result of both the improved observation resolutions of the radar and the rain gauge measurements inside the model area. In spite of the difficulties for the rain gauge settings in the urban area, the rainfall input and model output from this gauge deviated less from the radar output.

The model results with respect to the use of spatially averaged radar data compared to the spatially variable radar are remarkable. Despite equal rainwater volumes in the model area, the simulated water at street volumes varied widely. The appropriateness of spatially averaged input to represent the spatial variability in the model area turned out to be dependent on the characteristics of the particular events. For rainfall events with high rainfall depths in just a few radar pixels in the model area, the spatially averaged input have not always resulted in water excess. Next to this, the water at street volume generated by the spatially averaged radar is generally lower compared to the volumes of the spatially variable radar. The local high rainfall depths, which are most important for the water at street generation, have often been averaged out in the spatially averaged radar. Therefore, it is concluded that the rainfall and water at street situations in sensitive areas can be represented in most detail with the use of the spatially variable radar data.

According to the current model behaviour, the identified differences in the rainfall input are enlarged in the water at street simulations. The explanation can be found in the importance of the additional rainfall since it cannot be drained anymore by the sewage system. This way, the sometimes small differences in rainfall depth contribute most to the simulation of surface runoff.

Besides the spatial variability, other aspects have been identified in the model results that have affected the model outcomes and its differences. First, the outcomes showed that the model results are dependent on the rainfall intensities for the generation of water at street. As soon as the sewage system is filled, the remaining high rainfall intensities in the event will determine the final water at street volume to a great extent. Therefore, the seriousness of the water at street appears to be related to the rainfall intensities. This also explains many of the differences between rain gauge and radar runs with almost equal rainfall depths. Since the observed rainfall of the rain gauges generally occurred in shorter rainfall durations, more or longer periods with high intensities are present in the data. As a consequence, the simulated water at street is sometimes significantly higher than in the radar model runs. Overall, it is difficult to identify the most reliable rainfall estimation due to the lack of detailed information concerning water at street and the uncertainties in the model calculations. More considerations with respect to the study results will be discussed in the following chapter.

6 DISCUSSION

The study outcomes should be interpreted with caution due to several limitations in the research. Influencing factors comprise the uncertainties in the rainfall input and the model behaviour. After considering these aspects, it is possible to discuss the value of weather radar application in rainfall-runoff models regarding urban water management and its corresponding water tasks in particular. This includes a short preview of possible measures for the reduction of water inconveniences, which is based on influential model parameters. The following questions are treated within this chapter:

5. *What is the meaning of the model output differences between weather radar and rain gauge considering reliability of both the model and the data?*
6. *Which possible measures can be described that correspond to identified influential model parameters?*
7. *What are the implications of weather radar application on the urban water tasks and does the use of radar data hold added value for urban water management in general?*

6.1 Significance of model results in view of reliability

The obtained model output in the previous chapter often showed widely varying water accumulation between rain gauge and radar input sources. Next to the different model behaviour, which is described later on, this may be attributed to the origin and reliability of the rainfall data itself.

6.1.1 Rainfall data reliability

The reliability of the rainfall data is of major importance for the study results since they propagate through the model and affect the generated water at street situations. For the automatic hourly rainfall station Soesterberg of the KNMI, the reliability of the data is assumed to be good as it complies with all prescriptions for accurate point measurements (KNMI, 2000). Since 2009, rainfall information from inside the urban area of Amersfoort has been used. Although this rain gauge in the centre of the model area does not meet all the requirements for accurate measurements, the retrieved rainfall depths correspond well with those of nearby daily rain gauges of the KNMI over a period of 9 months (see table 2-1 in paragraph 2.3.2). Still, these rainfall depths differ between each other due to the spatial variability of rainfall. This effect becomes stronger for the short term since the spatial variations tend to average out on the long term (Overeem, 2009). Therefore, it is difficult to determine the reliability of rain gauge measurements for the short term rainfall events in this study. For now, sufficient reliability is assumed on the basis of the credible 9 months rainfall depth. However, the effect of the current urban settings on the measured values needs to be examined more extensively to guarantee reliable future use. Measurements in the close surroundings of the urban rain gauge may be helpful for this examination as it excludes possible effects of spatial variability to a great extent.

With respect to the radar data, different studies (Overeem, 2009 and Seo et al. 1999) showed that the quality of the rainfall information of raw radar data is insufficient for truthful application in models. However, the applied rainfall data in this study have been corrected by means of a picture from daily rainfall depths of KNMI stations with a network density of 100 km^2. After this calibration, the reliability of the rainfall information from weather radar appeared to be good (Overeem, 2009).

Besides the reliability aspects of the rainfall information, it should be mentioned that this study compares point measurements with spatial radar data. First, these two data sources have different spatial resolutions which hamper fair comparisons in principal. The representation of very local extreme rainfall depths attenuates for increasing spatial scales of the radar. Therefore, this aspect is more important for the radar observations in the period 1998-2009 with a spatial resolution of 2.5 kilometres. Furthermore, the employed radar data are dependent on the rain gauge information since the radar data calibration is based on the rain gauge measurements of both daily and hourly stations of the KNMI. Therefore, the study has actually assessed rain gauge data in comparison to radar data that has been adjusted with rain gauge information. Possible errors in the rain gauge measurements are consequently also incorporated in the used radar data. So, despite the divergent values in the rainfall accumulations of the two input sources, they cannot be considered independently from each other.

6.1.2 Model reliability and uncertainty

The storage capacity of the sewage system is for the major part of the model area assumed to be 7 mm. In areas where additional storage facilities affect the storage capacity, an additional amount of rainfall is assumed on top of the default 7 mm. This simplification could mainly be ascribed to the absence of detailed information of sewage inflow and discharge in a sewage system model. For the same reasons, the sewage discharge is set to a fixed value of 0.7 mm/h. However, the many variations in elevation and accompanying slopes in the sewage system cause various water velocities in reality. Based on the results of the sensitivity analysis, some errors in the sewage discharge do not seriously affect the model outcomes. Other parameters seemed to be more important, such as the infiltration parameter.

The infiltration parameter prescribes infiltration capacities for the land use categories from the land use map. This is already an error source since all raster cells have to be classified in the six available land use categories. Furthermore, the knowledge of infiltration processes in the urban area is restricted with respect to paved and semi-paved surfaces (Villarini et al., 2010). This is mainly due to the lack of infiltration measurements, which also explains the absence of infiltration data in the case study of Amersfoort. According to the study of Van de Ven (1989), the infiltration capacities of paved surfaces vary from 0 mm/h for asphalt road types up to possibly 30 mm/h for brick pavement types. Therefore some assumptions within this range have been simulated. However, these assumptions are very decisive as differences of a few mm for the infiltration parameter already have big influences on the model results. The errors in this parameter have been challenged by using the most appropriate values according to the experiences in the model calibration. In its turn, the validation of these model settings has been hampered by a lack of detailed water at street information (location and extent of inconveniences) of historical events. The assumed suitable settings have been acquired by the use of events that did just or did just not cause water excess. It may be clear that more accurate rainfall and runoff observations, including infiltration processes, for extreme events in urban areas are required (as concluded in Villarini et al., 2010) to enable the development and application of more accurate models in the future. A decrease of simulation errors in the model will provide more detailed pronouncements upon bottlenecks in the drainage system.

Uncertainty with respect to the allocation of water excess over the model area is caused by the pit criterion. This parameter is used as a steering variable in order to optimize the number of water at street locations for historical events. Again, the limited water at street data complicate the possibilities for setting the pit criterion. Therefore, a value is used for which the number of water at street locations corresponds best with the identified water at street locations by the area experts. In this research the pit criterion is considered less important since the quantitative analysis have been performed on the basis of water at street volumes, which are independent from the pit criterion.

6.1.3 Required model adjustments

For future use of the model, improvements regarding the development of water at street through time are required to obtain a more realistic end situation. First of all, more appropriate values or changed model concepts with respect to the pit criterion are beneficial for future use of the model. This will provide a more realistic generation of water at street. Secondly, adjustments to the sewage storage are desirable. If the storage of the sewage system is sufficient again after a dry or drizzle period, the inundated areas should be able to start the drainage into the sewage or soil. This way, the water at street situations can diminish during the rainfall event, which will lead to more realistic model output and improved reliability. Implementation of a sewage system model will be essential for this adjustment as knowledge concerning the sewage inflow is currently too uncertain.

Furthermore, the time step of the model needs to be decreased to prevent the allocation of large water volumes to a pit. In the executed model simulations still cells exist for which water depths of several meters are attributed. In reality, this is of course impossible as the water will be wider distributed over the surrounding surfaces. However, the decrease of the model time step with a factor 2 or more will also increase the model calculation time with comparable factors. This is undesirable as the feasibility of the model comes into play. The use of more powerful computers may bring help for this issue.

In view of all uncertainty sources mentioned above, it is important to consider the feasibility and limitations of the model in conjunction with the study objective. Since the study aimed at obtaining an impression of water at street situations and their extent for relative comparisons between various input sources, the model is assumed to be appropriate. Moreover, accurate inundation depths or water at street durations are not required in this research.

6.2 Identification of measures according to influential model parameters

By means of the experiences during the sensitivity analysis, some possible measures will be briefly discussed here. The further identification and testing of effective measures goes beyond the purposes of this study in consequence of the limited extent of the sensitivity analysis and the early phase in the model development.

The compliance with the urban water tasks requires solutions for bottlenecks in the urban drainage system. Possible measures to diminish the occurrence of water at street are mainly based on the outcomes of the sensitivity analysis in which influential parameters have been distinguished. These parameters are translated to measures with the best abilities to affect the values of the identified parameters. The following parameters have been identified that influence the water at street volume most effectively:

- Infiltration capacities
- Sewage system storage

As mentioned before, sewage storage interventions are often unattractive in comparison to measures above the surface due to the required investment costs and nuisance for the neighbourhood. Nevertheless, in the past years several additional storage facilities have been implemented in the urban area of Amersfoort. In the future, more storage facilities are planned. This kind of measures may further restrict the occurrence of water at street and appeared effective in decreasing the occurrence of rising manhole covers at bottlenecks in the drainage system. Here, the emphasis is put on possibilities to increase the infiltration rates in the urban area. According to the obtained infiltration values in the model calibration (see table 4-7), the most decisive categories consists of buildings and paved roads. Most improvements can be gained by means of interventions affecting these two categories.

In fact, the measures can be assigned as source control techniques since they reduce the quantity of runoff from the site (Environment Agency, 2003). The following measures can be distinguished:

Green roofs
By the implementation of green roofs, the volume and rate of runoff to the drainage system can be reduced. The green roofs absorb rainfall water and delay the discharge towards the downpipes. Therefore, this measure can be used to flatten out the usual high and quick discharge peaks in the urban area. Besides, the green roofs have benefits for water quality, environment and insulation. Conversion of conventional flat roofs to green roofs is often possible without exceeding design loadings of the buildings (Environmental Agency, 2003).

Rainwater butts
Reduction of discharge from roofs towards the sewage system can also be reached by the use of rainwater butts. These butts harvest the storm water and may be used to water plants. It is important to guarantee sufficient storage capacity of the rainwater butts for coming rainfall events.

Permeable pavements
Paved surfaces, like asphalt roads, have restricted infiltration capacities. In case of high rainfall intensities this quickly results in infiltration surpluses and corresponding surface runoff. Permeable pavements provide an alternative to the conventional pavements as the permeability of the surfaces can be increased considerably. They can be made from gravel, grasscrete, porous asphalt or certain kinds of concrete blocks. Next to the surface, also the sub-layer needs to be designed for the permeable function. If the conditions are suitable, the water may be allowed to infiltrate directly into the subsoil (see the example in Figure 6-1). This is particularly appropriate for lightly contaminated runoff, close to source (where the rainfall has fallen on the surface) in for example pedestrian areas or parts of residential districts.

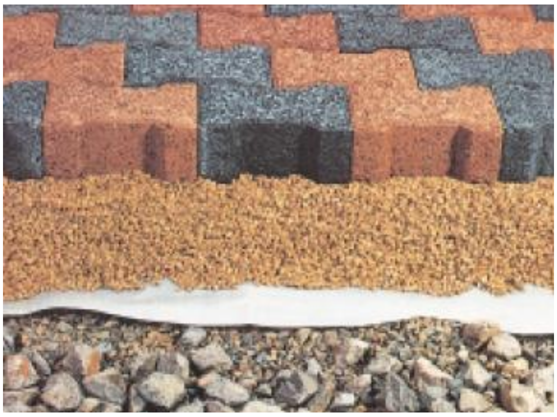


Figure 6-1: Porous blocks laid on a bed of ground and crushed stone. The sub surface layers provide useful storage volume for extreme rainfall events.

For roads which are used intensively by motor vehicles, a reservoir can be constructed beneath the pavement in which the water is stored for reuse, infiltration or delayed discharge. The permeability of the subsoil and the extent of the storm water contamination is directive for the needs of the sub surface part.

Of course, also the creation of more green in the urban area is an effective measure to improve infiltration rates. This is especially effective if permeable vegetated areas replace paved or built-on surfaces.

6.3 Implications of study results for urban water management

One of the most important elements of the urban water tasks is to act on problems more than on legally laid down frequencies of occurrence for water inconveniences. Since the weather radar is able to show local heavy parts in specific rainfall events, its information seems to be suitable for use in analysis and simulation of urban bottlenecks. The spatially variable information may contribute to the explanation of water excess in certain parts of the city. On the other hand, the measurements of one or a few rain gauge stations may not provide the explanation of possible water at street situations. Events assumed to be quite regular according to nearby rain gauge stations, can therefore be considered differently with radar rainfall data.

In addition to the analysis of the rainfall data itself, the use in rainfall-runoff models provides advanced insights of urban drainage responses to the spatially variable rainfall. Rainfall events may for instance result in one or a few water at street locations in the urban area. On the basis of spatially uniform rain gauge model input, it may be assumed that some bottlenecks exist in the urban drainage system. However, the water inconveniences turn out to be the consequence of local extremes if the situation is simulated with radar data. In this case the rainfall depths locally exceed the normative amounts. With the availability of this more detailed knowledge for the urban water managers, the cause of water excess may be explained and appropriate solutions can be provided.

An example from the model simulations for Amersfoort showed that rain gauge information has not been able to explain the occurrence of water at street in several rainfall events, for example July 28 2006 (see results in chapter 5). It appeared that water inconveniences may be expected in view of the radar data and yet the working of the urban drainage system could be according to the legal prescriptions. With the availability of more radar data in the coming years, it may become necessary to adjust the rainfall events in the legal prescriptions. The current normative rainfall event with a return period of two years could be replaced by an event with a certain degree of spatial variability within the urban area. This will reveal possible occurrence of water at street in perspective of local rainfall variations, which represent a more realistic situation. Therefore, the decision whether measures should be taken or not will be considered in a significantly different context. Instead of structural adjustments to the urban sewage system, some local measures, for example a retention pond or infiltration facility, could be implemented to improve the robustness of the drainage system in specific districts. Thus, the use of more detailed data in space gives opportunities for more efficient water management while saving expenditures for non required measures.

6.4 Outlook

High resolution rainfall data, provided by a combination of radar and rain gauge observations, can contribute to the knowledge of the urban drainage system. This study has shown that besides high resolution data, also the model behaviour is to a great extent responsible for the results and possible conclusions. For example in urban areas, important processes such as infiltration and water storage during extreme events are still poorly understood. This hampers the model accuracy and controlling abilities in the urban water management. Therefore, detailed measurements of runoff processes in the urban area are required to enhance the performance of rainfall-runoff models in the future. This mainly includes infiltration processes on paved surfaces and discharges via the sewage system.

Future models may also use updated elevation maps in which several errors have been removed. Besides, the application of more sophisticated models should incorporate interception processes by vegetation or buildings. Overall, the radar based tools in urban water management may be boosted by the restriction of uncertainties from rainfall information and model behaviour, as well as by increasing radar time series. The latter may ask for more extensive investigation into the influence of radar data on the normative rainfall events for urban water management. This can prove the necessity of the adjustment of normative rainfall depths and the integration of local rainfall variability in the design and testing of urban drainage systems. Concluding, it is likely that the application of radar data will dispel the use of spatially uniform data more and more.

7 CONCLUSIONS & RECOMMENDATIONS

With the help of all the gained information in the previous chapters, this chapter will present the conclusions for the research questions. Moreover, an overall conclusion is provided in which the research objective is satisfied. Finally some recommendations are discussed with respect to the future model use and required follow-up research.

7.1 Conclusions

7.1.1 Conclusions research questions

1. To what extent does the total rainwater volume in the study area for the identified events of the weather radar data and rain gauge data correspond to each other?

The investigation of extreme rainfall events for the radar data and the corresponding information of the rain gauges in chapter 3 have revealed vast differences between observations of the two rainfall estimators. For the twelve identified events, the average difference between the rainwater volume of the rain gauge and radar data is 50% with a range from 0.4% to 193.2% (see Table 5-1). Especially the differences for the situation before 2009 are remarkable, probably because rain gauge measurements from outside the model area have been used. The average difference for this period is 70%. The rainwater volumes differed less (on average 22%, ranging up to 67%) for the rainfall events in the period 2009-2010 with rain gauge measurements in the centre of the model area. Based on these outcomes, it can be stated that rain gauges outside the urban area in view are inappropriate to represent the rainfall within that urban area.

2. Is the spatial distribution in the identified events meaningful for the simulation of water at street in comparison to a spatially averaged rainfall depth for the whole study area?

Despite the equal rainwater volumes for spatially averaged and spatially variable radar, differences in modelled water at street range from 2 to 100% with an average of 24% (chapter 5). This can be explained by the spatial distribution in the rainfall input of spatially variable radar. Especially locally high rainfall intensities turned out to be decisive for the extent of generated water excess. Model input from spatially averaged radar has averaged out these decisive local variations. For the period 1998-2008, the low spatial resolution of 2.5 km restricts the recognition of clear spatial rainfall patterns in the urban area. This resulted in smaller but still significant differences between the radar data sources. Hence, using the spatial variability in rainfall distribution for the input of rainfall-runoff models will minimize the possible loss of essential local rainfall information.

3. **What are the effects of the use of radar rainfall information with its higher spatial resolution on the simulated water accumulations in the study area in comparison to the results based on rain gauges?**

Based on a comparison of the radar rainfall maps and the rain gauge information, it already appeared that considerable differences are present in the rainfall volumes. For all the analysed events, these rainfall data differences have been enlarged in the simulated water at street situation. Overall, the model results have revealed a considerable influence of spatially distributed rainfall input on the simulated water at street. The local variations of the rainfall depth can clearly be noticed in the picture of the inundation maps. For the comparison of model results from spatially variable radar and uniform rain gauge input, differences range from 36% up to a situation in which 68 times more water excess has been simulated by the rain gauge data. The most extreme variations occurred for the rainfall events before 2009 for which the radar rainfall values within the model area deviated in some cases significantly from those at the location of the rain gauge outside the model area.

4. **What is the dependency of the model results on the specific properties of extreme rainfall events and influencing areal characteristics?**

Besides the rainwater volumes, other specific properties of rainfall events have affected the model output, such as rainfall patterns, high rainfall intensities and characteristics of the urban area.

The applied equation of the spatial variability does not explain the particular locations and distributions of locally heavy rainfall within the model area. Therefore, it does not make a distinction between rainfall in more or less sensitive areas. However, especially rainfall peaks in sensitive areas appeared to be important, for example in the city centre with its high percentage of paved area. Also by reason of the rainfall pattern, the particular rainfall depth at the gauge location may give a distorted picture of the rainfall in the model area. Moreover, the model output does not only depend on the total rainfall amounts as shown in some cases of almost equal rainfall depths for the rain gauge and radar input. Here, the rainfall durations in the rain gauge data were generally shorter and hence intensities were higher. The latter has increased the generation of water excess compared to the radar data for which rainfall has been spread more evenly over the total event time.

Besides rainfall properties, the model results depend on several characteristics of the urban area. In particular the percentage paved area, characteristics of the sewage system and surface slopes can be mentioned. It is assumed that these aspects affected the study results to a limited extent since not the absolute outcomes but the relative differences have been assessed.

5. **What is the meaning of the model output differences between weather radar and rain gauge considering reliability of both the model and the data?**

First of all, it should be realized that the radar data is not independent of rain gauge data as rain gauge measurements are used for the calibration of radar data. Furthermore, the rain gauge recordings of Amersfoort do not meet the official prescriptions for accurate observations (see chapter 3). Nevertheless, the use of this data for the period 2009-2010 is legitimated by the little deviations from daily rain gauges in the surroundings of Amersfoort.

Besides uncertainty in rainfall data, the model also has some uncertainties. First, the calibration and validation process could be improved if more accurate and extensive information would be available of the historical water at street situations. Also the lack of information with respect to the sewage system characteristics and the infiltration capacities in the urban area hamper the model accuracy. Secondly, the simulation outcomes of especially longer duration events should be interpreted with caution due to irreversible accumulation of water at street in the model calculations. This complication has been taken into account by considering the final water at street situations as totally occurred water excess during the event instead of the realistic final situation. Furthermore, the model accuracy is limited by the allocation of unrealistic water volumes to some raster cells. This prevents a better distribution of the total water volume over surrounding surface. However, absolute inundation depths are unimportant in view of the study objective as a relative comparison between results of radar and rain gauge input was intended.

6. **Which possible measures can be described that correspond to identified influential model parameters?**

By means of the rough sensitivity analysis, some parameters have been identified that most significantly affect the model outcomes. The most sensitive parameters are the infiltration and sewage storage parameter. With respect to the latter one, already several interventions to the sewage system have been implemented, such as additional storage facilities. Considering the infiltration parameter, various measures above the surface can be made to improve the infiltration capacity. Permeable pavements, rainwater butts and green roofs are examples of measures that restrict the inflow to the sewage system by retaining the water at source (chapter 6).

7. **What are the implications of weather radar application on the urban water tasks and does the use of radar data hold added value for urban water management in general?**

According to the current policy in urban water management, the approach of specific problem areas is preferred over the maintenance of normative safety levels in the whole urban area. The results in this study have complied well with these demands since the radar data has enabled the reflection of local extremes in both observed rainfall and simulated water at street. This could be helpful for the identification and analysis of local bottlenecks in the urban area. With this knowledge, water managers are able to propose tailor-made solutions, which prevent the implementation of extensive structural adjustments to the sewage system. Some local measures could be sufficient to efficiently deduce water inconveniences, which saves non required expenditures. In addition, the simulation of spatially distributed rainfall, possibly artificial, can be helpful to test the response of the urban drainage system. Based on the above-mentioned, weather radar application could have an added value for urban water management. Increasing radar data series in the coming years may even ask for adjustment of normative rainfall events in order to integrate the spatial variability.

7.1.2 Overall conclusions

The use of radar rainfall information has shown different degrees of spatial variability in the study area, especially since 2009 with the availability of improved spatial and temporal resolutions. Sometimes significantly different rainfall depths have been obtained in comparison to the data of the employed rain gauge station. These differences are enlarged in the simulated water at street volumes of the rainfall-runoff model. The location of the rain gauge appeared to be an influential factor for the observed rainwater volume. Therefore, rainfall observations outside the urban area are supposed to be inappropriate for rainfall estimation inside the urban area. Other rainfall properties as rainfall intensity and duration have also shown their importance for the model output. The assessment of the spatial variability in the comparison between spatially averaged and spatially variable radar showed that locally high rainfall depths have sometimes been averaged out by the spatially averaged radar input. This emphasizes the need of spatially variable rainfall input to prevent loss of essential local rainfall information. Implications of radar information on urban water management comprise a problem-based approach, which is in correspondence to the current policies. Radar input for rainfall-runoff models is helpful to identify and explain water at street occurrence in view of local rainfall variability. Besides the historical events, events with artificially added spatial variability can be simulated to test and predict the response of the drainage system. These applications give possibilities for more effective and appropriate measures like local improvements of the infiltration by permeable pavements. This way, it will save non required expenditures for drastic measures all around the urban area. The above-mentioned applications demonstrate the added value for application of radar data in urban water management. Moreover, longer time series of radar data in the coming years will provide possibilities to investigate the need for integration of rainfall variability in normative rainfall events.

7.2 Recommendations

7.2.1 Recommendations for urban water management

- The use of uniform rainfall data for urban water management hampers the recognition of spatial distribution in rainfall. The use of spatially variable radar is recommended to overcome this limitation of rain gauge information. Based on this study, the added value of radar data is explained by better opportunities to identify and analyse bottlenecks in the urban drainage system. Consequently, it can contribute significantly to the problem-based approach in the urban water tasks.

- In addition to the radar information, the use of some rain gauges in the urban area may still be desired for detailed point measurements. Rainfall observations outside the urban area are not recommended due to the possible deviations from the rainfall within the urban area. On the other hand, the rain gauge observations in urban settings are often not in accordance with the prescriptions for accurate measurements. The effects of these settings need to be examined more extensively to ensure reliable future use of the gauges. For this reason, additional measurements at suitable locations may be helpful to monitor disturbing effects of for example buildings. These reference observations should be taken in the close surroundings of the examined rain gauges to exclude effects of spatial variability to a large extent.

- In favour of the urban water tasks, the occurrence of water inconveniences during heavy rainfall events can be predicted by simulations of the rainfall-runoff model. However, the calibration and validation of the rainfall-runoff model are currently hampered by the limited information regarding historical water at street situations. For this purpose, databases with more detailed recordings of water at street situations should be maintained. Next to this, satellite images just after the event may provide a clear picture of serious water at street locations. By means of these observations, a better understanding of the condition of the urban drainage system can be obtained. In general, more measurements of important rainfall-runoff processes are recommended to support decision-making in urban water management.

7.2.2 Scientific recommendations

- In addition to the detailed water at street observations by municipalities, also advanced knowledge is required concerning important processes such as infiltration, water storage and interception by vegetation or buildings. Research of these processes is recommended to enhance the detail level of rainfall-runoff models for the urban area.

- Smaller time steps can be implemented in the model to improve the allocation of water at street in the model calculations. It should be mentioned that adjustments regarding the detail level, will require the application of powerful computers to limit the model calculation time.

- Since the results of this study are based on one urban case study, the conclusions are also dependent on characteristics of the urban case. For other cities, specific properties like the percentage paved area or the variations in altitude will affect the model outcomes. Also the availability of rain gauge measurements will be different. Nevertheless, it is assumed that the relative outcomes of this study are mainly universal. For more support of the drawn conclusions, research in other urban areas is recommended.

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APPENDIX A RESEARCH MODEL

Below, a schematic and visual representation is given of the steps that have to be taken to reach the objective of this study.

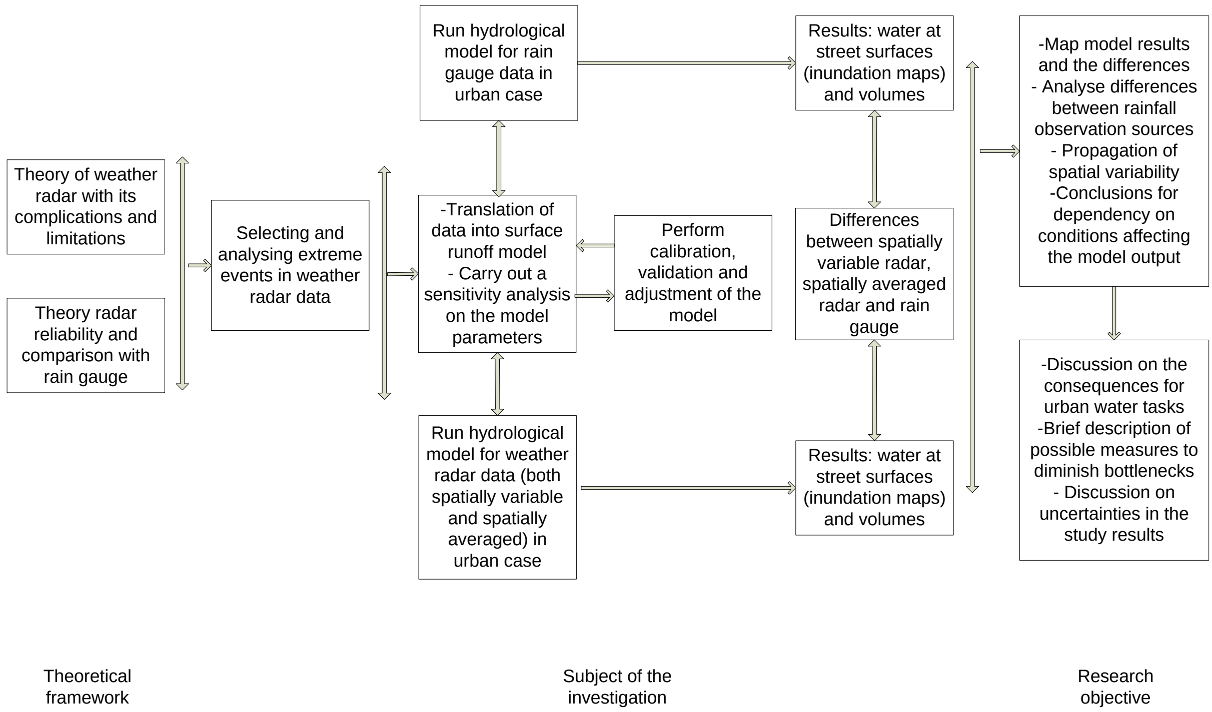


Figure A-1: Schematization of the research model.

APPENDIX B ERROR AND UNCERTAINTY IN RAINFALL ESTIMATES

Since the rainfall images require a two-dimensional representation of the precipitation, they represent a cross-section at a constant altitude of 800 m above the earth surface. Therefore, the radar image may overshoot precipitation from lowly situated cloud systems, like drizzle (Holleman, 2003). Other important aspects with respect to the uncertainty of radar observations are listed below (Overeem, 2009):

- Beam-blockage, e.g. buildings or trees relatively close to the radar station blocking the lowest radar beams. This has influence at longer distance from the station where the lower cloud systems and its precipitation may not be observed anymore. Also geomorphologic patterns can cause shielding or beam blockage and may result in non meteorological echoes called ground clutter.
- Overshooting; at longer ranges overshooting of cloud systems is caused by the curvature of the earth's surface. This effect is a decisive factor for the applicable range of the radar.
- Attenuation; this will lead to underestimation of precipitation, especially at longer ranges.
- Non-uniform vertical profile of radar echoes.
- Hail effects; these occur especially with very high rainfall rates of 100 mm/h or more.
- Natural variability in drop-size distributions; an important source of uncertainty in radar measurements of precipitation. This is particularly dependent on the season (Joss & Waldvogel, 1990).

Whereas the random errors in the radar rainfall data tend to average out at larger spatial-temporal scales of aggregation, the systematic errors do not. The resultant bias, the systematic departure from the true and unknown rainfall, makes the direct use of radar rainfall data in quantitative hydrologic models extremely difficult (Seo et al., 1999). These radar errors are often due to lack of calibration and inaccurate relationships between rainfall intensity and radar beam reflectivity. So, identification and estimation of the bias in radar rainfall estimates is essential to restrict the measurement errors (Krajewski & Smith, 2002).

On the other hand, a growing recognition exists that precipitation estimates from historical rain gauge data are of doubtable quality concerning most of the 15-minutes, hourly and daily rainfall data. This could particularly be ascribed to a lack of fault detection in the rain gauge measurements. Appropriate corrections to the gauge data have been hampered by the spatial variability of rainfall which has caused significant differences between surrounding rain gauges (Krajewski & Smith, 2002). Overall, the spatial inaccuracy of the rain gauge measurement is a main disadvantage, caused by insufficient density of the gauge network. Therefore, the use of radar data may lead to much better and more detailed estimations of spatial rainfall variability (Einfalt et al., 2004). Besides, locations that meet all the setting requirements for rain gauges are often difficult to find in urban areas. According to the guidelines of meteorological observations by the KNMI (2000), the neighbourhood of the measurement site must be free of objects that could affect the measurements. For example no obstacles like trees may be placed within a radius of 100 metres. Next, a radius of even 400 metres is required for obstacles such as sheds or buildings.

APPENDIX C IDENTIFIED RAINFALL EVENTS BASED ON EXTREMENESS

Table C-1: Selected rainfall events on the basis of extremeness for the period 1998-2008.

Event date	Time start	Duration (hours)	Max rainfall amount * (mm)	Comments
June 15, 1998	15:00	1	15.3	Very local, around city centre
September 9, 1998	16:00	1	15.9	Below 10mm in model area
June 7, 1999	20:00	1	15.8	Criterion exceeded in area of interest
July 29, 2000	13:00	1	24.3	West and south-western part of the city
August 7, 2001	4:00	1	19.7	Well over criterion in whole model area
September 17, 2001	16:00	4	25.8	Spatially uniform distribution
August 16, 2004	4:00	4	27.5	Criterion not exceeded in area of interest
June 30, 2005	0:00	4	27.9	Spatially uniform distribution
November 25, 2005	12:00	4	25.9	Spatially uniform distribution
July 28, 2006	19:00	1	18.5	Part of very extreme event at the south of Amersfoort
July 28, 2006	20:00	1	29.6	Propagated northwards with highest intensities in the northern part of Amersfoort
July 28, 2006	17:00	4	40.4	Well over criterion in whole urban area
July 5, 2007	2:00	4	30.9	Especially in southern part of Amersfoort
June 3, 2008	0:00	1	21.4	Spatial uniform distribution
September 12, 2008	13:00	1	21.5	Spatially variable in the south-western part of Amersfoort
September 12, 2008	13:00	4	31.4	Criterion exceeded in model area

* Value in one radar pixel for the duration of the rainfall event.

Correspondingly, the events for the period 2009 through August 2010 are listed in the table on the next page. Some additional properties of the events could be revealed, because of the increased spatial and temporal resolutions.

Table C-2: Selected rainfall events on the basis of extremeness for the period 2009-2010.

Event date	Start time	Duration (min)	Maximum intensity* (mm/hour)	Average rainfall amount in whole area (mm)	minimum observed amount (mm)	Maximum observed amount (mm)
May 26 2009	4:05	120	114.3	16.6	10.2	22.5
Frequency of occurrence**				1x per year	5x per year	once per 3 year
July 22 2009	22:30	120	23.0	13.2	11.1	14.3
Frequency of occurrence**				2 x per year	3-4x per year	2x per year
August 28 2009	20:10	120	66.4	14.8	13.7	15.6
Frequency of occurrence				1-2 x per year	2x per year	1x per year
August 28 2009	20:10	240	66.4	23.7	22.0	25.1
Frequecy of occurrence**				0.5-1x per year	1x per year	once per 2 year
July 10 2010	22:00	180	235	37.8	32.8	47.7
Frequecy of occurrence**				once per 15-20 year	once per 10 year	once per 50 year
August 4 2010	15:00	60	85.5	11.6	7.7	14.4
Frequecy of occurrence**				2 x per year	5 x per year	1 x per year
August 26 2010	5:00	720	28.0	40.5	34.0	46.3
Frequecy of occurrence**				once per 5 year	once per 2 year	once per 10 year

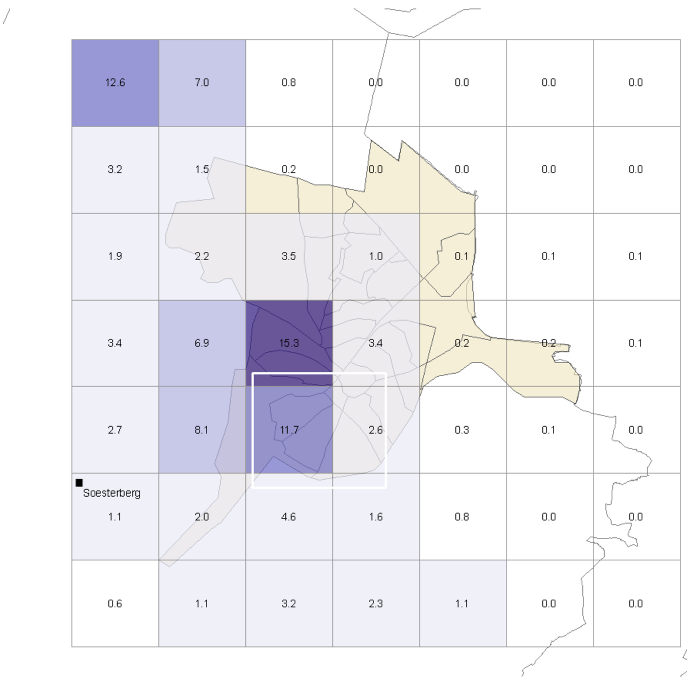
* Based on once per 5 minutes observations in one radar pixel

** Approximate values from statistics of weather station De Bilt ([Smits et al., 2004][Buishand & Wijngaard, 2007]).

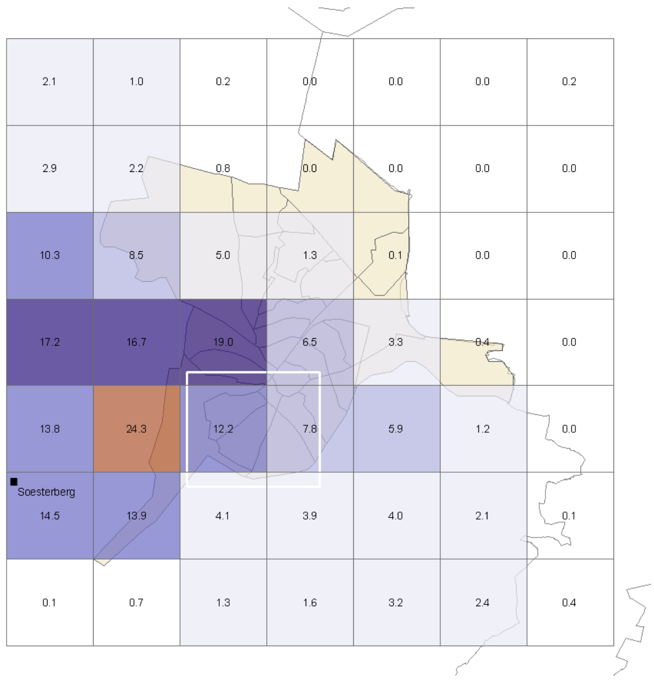
The durations have been rounded off to the nearest hours to enable a better comparison between the events and judgment on the basis of the criteria. However, the events may be selected for a shorter or longer duration in favour of the model simulations.

APPENDIX D RAINFALL ACCUMULATION MAPS

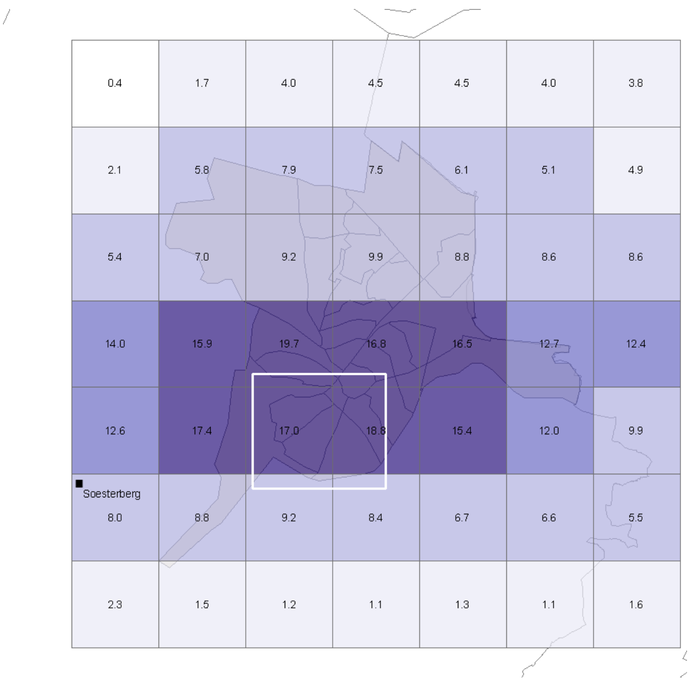
Rainfall depths for the events in the period 1998-2008 (2.5 km grid) and 2009-2010 (1km grid). These maps may deviate from the model input since any rainfall for filling of the initial sewage storage is not included.

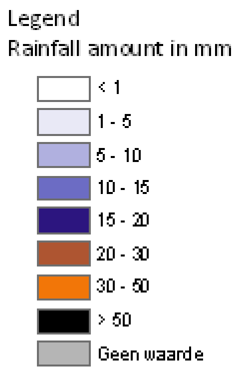


June 15, 1998 (15:00 – 16:00h)

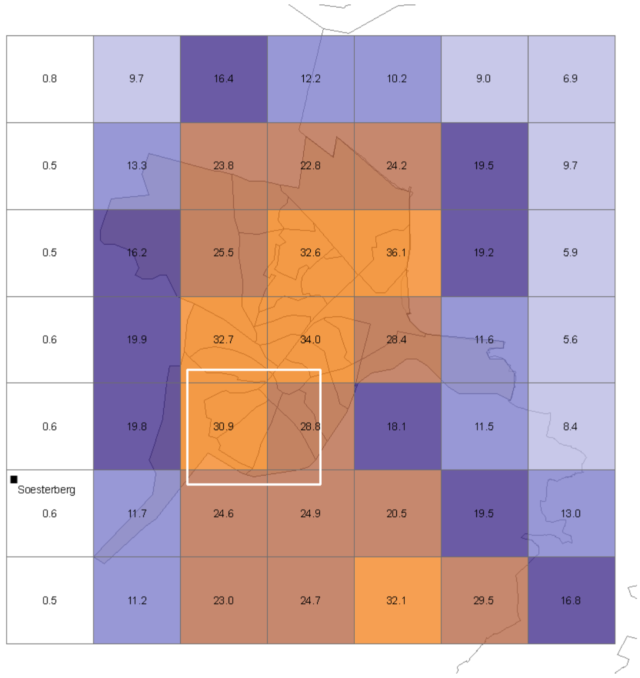


July 29, 2000 (13:00 – 14:00h)

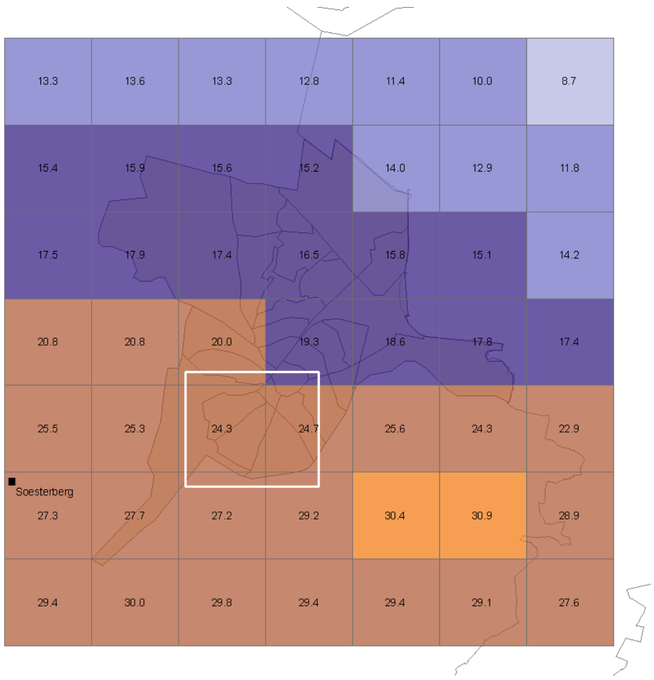




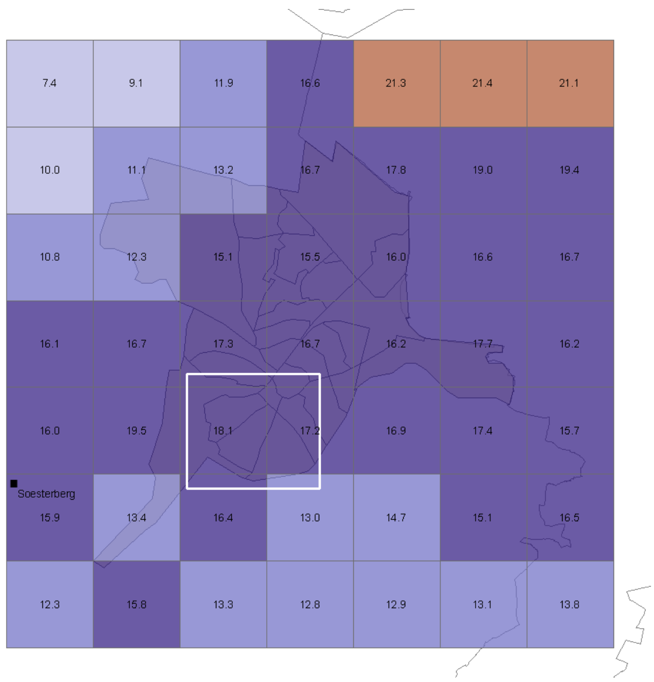
August 7, 2001 (04:00 – 05:00h)



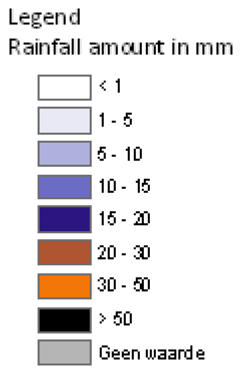
July 28, 2006 (17:00 – 21:00h)

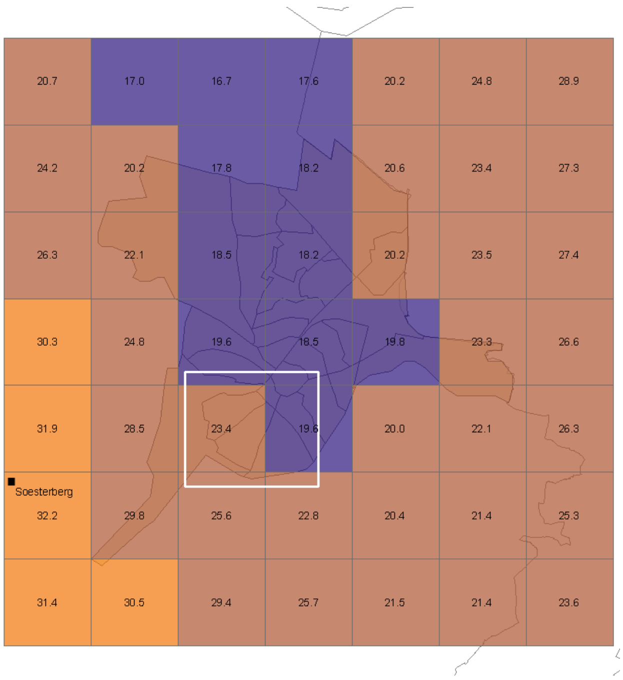


July 5, 2007 (02:00 – 06:00h)

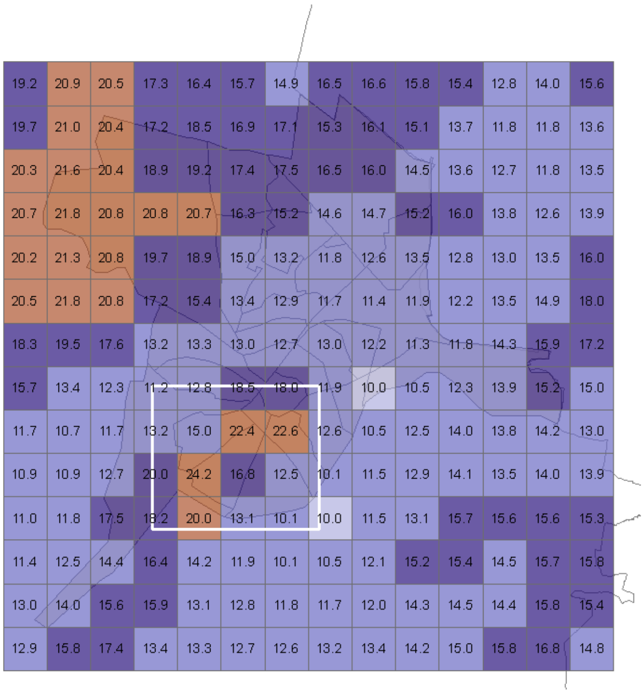


June 3, 2008 (00:00 – 01:00h)

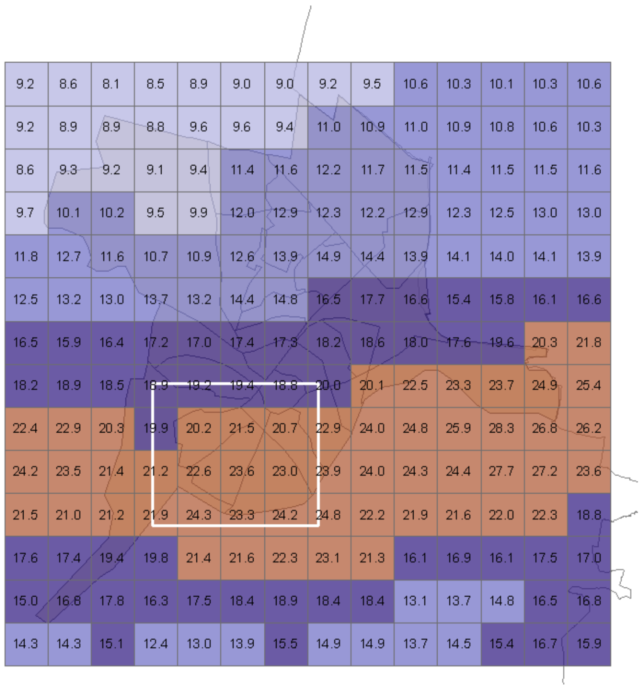




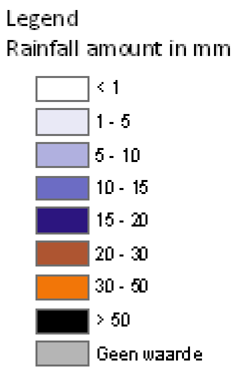
September 12, 2008 (13:00 – 17:00h)

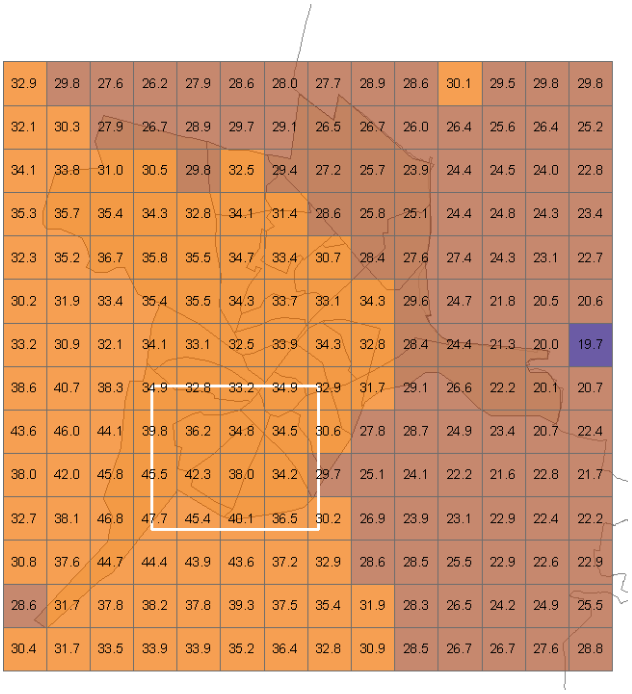


May 26, 2009 (04:00 – 06:00h)

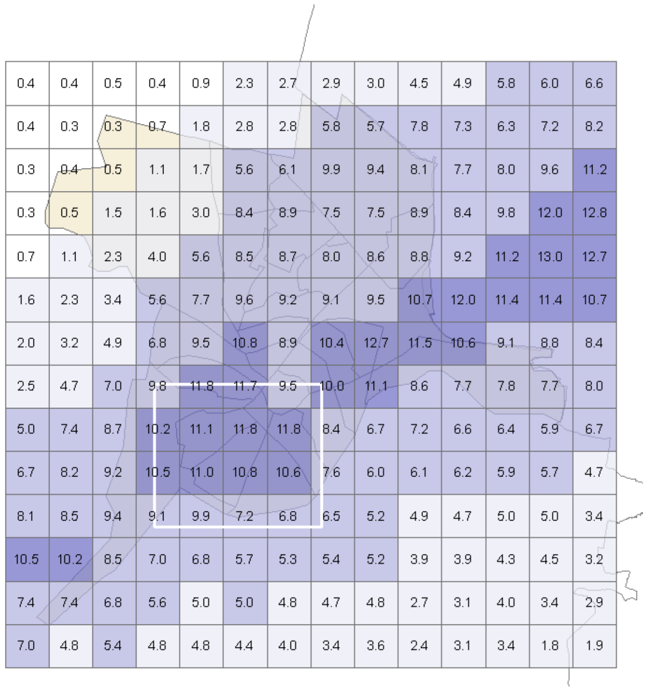


August 28, 2009 (20:00 – 00:00h)

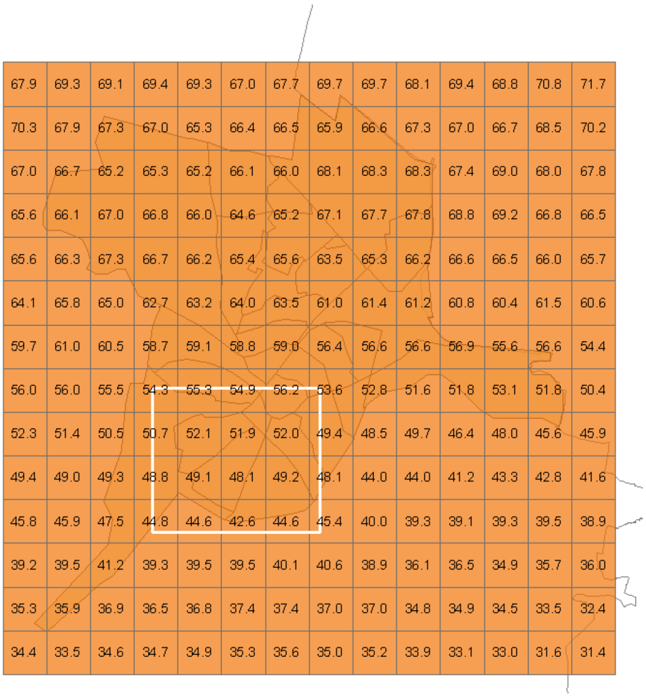




July 10, 2010 (22:00 – 01:00h)



August 4, 2010 (15:00 – 16:00h)



August 26, 2010 (5:00 – 17:00h)

Legend
Rainfall amount in mm

- < 1
- 1 - 5
- 5 - 10
- 10 - 15
- 15 - 20
- 20 - 30
- 30 - 50
- > 50
- Geen waarde

APPENDIX E EXPLANATION OF APPLIED INFILTRATION CAPACITIES

The justification of infiltration capacities for different land use types is given below:

1. **Buildings.** For buildings it is assumed that they are all connected to the sewage system. Therefore, the storm water will be discharged directly into the sewage until it is filled up completely. From this moment on (sewage surplus > 0), the rainfall depths will be added to the surface runoff and the infiltration capacity is 0 mm/h.
2. **Surface water.** It is assumed that all the precipitation at the location of the surface water can be stored in the surface waters. To integrate this in the model, a large infiltration capacity is assigned in order to avoid surface runoff from surface water locations.
3. **Paved roads, paved area.** This category can be divided into asphalt and different kinds of brick pavements. Asphalt is assumed to have an infiltration capacity of 0 mm/h while the infiltration of brick pavements can be considerably larger; capacities between 10 and 30 mm/h are normal (Van de Ven, 1989). For now 80% of the paved areas is assumed to be asphalt and 20% is assumed to be consisting of loose elements like clinkers with an infiltration of 10 mm/h in the standard run and 30 mm/h in the maximum run. Therefore the standard run will have an infiltration capacity of 2 mm/h. For the minimum simulation run 100% asphalt is assumed.
   For clinkers, the condition of the joints, the subsurface soil type and the size of the clinkers are determinative for the infiltration capacity. However, even for joints of old brick pavements which have been contaminated with silts, the infiltration rate is found to be good (Van de Ven, 1989).
4. **Unpaved roads.** The unpaved roads consist of sand and gravel paths in the natural areas in the city. The infiltration capacity is depending on the compaction of the soil. As it is assumed that these paths are intensively used by pedestrians and cyclists, the upper soil layer will be largely compacted and impermeable. The assumed infiltration rate is set equal to the level of brick pavements: 10 mm/h.
5. **Unpaved area, nature.** The infiltration capacity of parks or grass fields in the urban area are dependent on the soil type and the degree of vegetation which delays the moment the water will reach the soil. Assumption: Surface runoff from the green areas is not expected so its infiltration capacity is set on 100 mm/h in both the minimum and maximum simulation. This assumption is also legitimized by the sandy soils with locally some silt in the surroundings of Amersfoort (De Bosatlas van Atlas van Nederland, 2007).
6. **Remaining, semi-paved.** This land use type consists of different remaining areas in the city. For example gardens around houses, cemetery or some surfaces around paved roads. In general these areas are assumed to be semi-paved for which an infiltration rate of 10 mm/h is adopted for the standard run.

APPENDIX F RESULTS SENSITIVITY ANALYSIS

Table F-1: Results sensitivity analysis sorted on the basis of the effect on total volume of water at street.

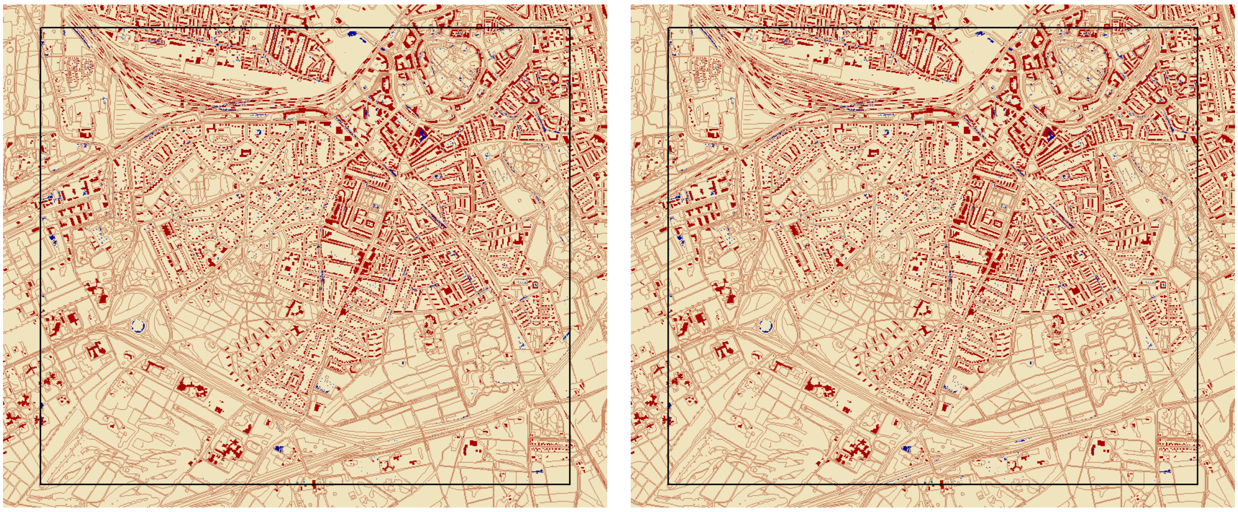
Order #	Model run	Total volume of water [m3]	Difference with reference [%]	Total inundated area [m2]	Difference with reference [%]	Assessed parameter
	reference run	29,792	-	91,925	-	
1	5	57,055	91.5	113,150	23.1	Infiltration rate: low
2	1	45,037	51.2	108,125	17.6	Initial sewage capacity: low
3	6	21,623	-27.4	80,225	-12.7	Infiltration rate: high
4	2	22,249	-25.3	78,875	-14.2	Initial sewage capacity: high
5	3	35,113	17.9	90,025	-2.1	Sewage discharge: zero
6	9	25,338	-15.0	83,575	-9.1	Evaporation
7	4	26,271	-11.8	84,800	-7.8	Sewage discharge: high
8	7	29,792	0.0	179,425	95.2	Pit criterion: low
9	8	29,792	0.0	85,675	-6.8	Pit criterion: high

Table F-2: Results sensitivity analysis sorted on the basis of the effect on total inundated area.

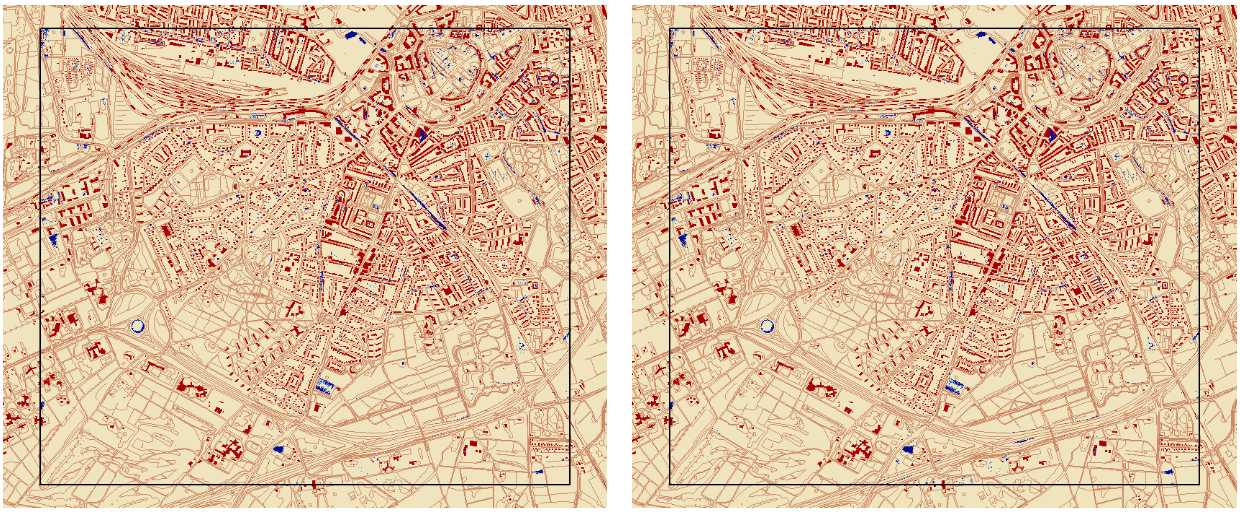
Order #	Model run	Total volume of water [m3]	Difference with reference [%]	Total inundated area [m2]	Difference with reference [%]	Assessed parameter
	reference run	29,792	-	91,925	-	
1	7	29,792	0.0	179,425	95.2	Pit criterion: low
2	5	57,055	91.5	113,150	23.1	Infiltration rate: low
3	1	45,037	51.2	108,125	17.6	Initial sewage capacity: low
4	2	22,249	-25.3	78,875	-14.2	Initial sewage capacity: high
5	6	21,623	-27.4	80,225	-12.7	Infiltration rate: high
6	9	25,338	-15.0	83,575	-9.1	Evaporation
7	4	26,271	-11.8	84,800	-7.8	Sewage discharge: high
8	8	29,792	0.0	85,675	-6.8	Pit criterion: high
9	3	35,113	17.9	90,025	-2.1	Sewage discharge: zero

APPENDIX G MODEL OUTCOMES: INUNDATION MAPS

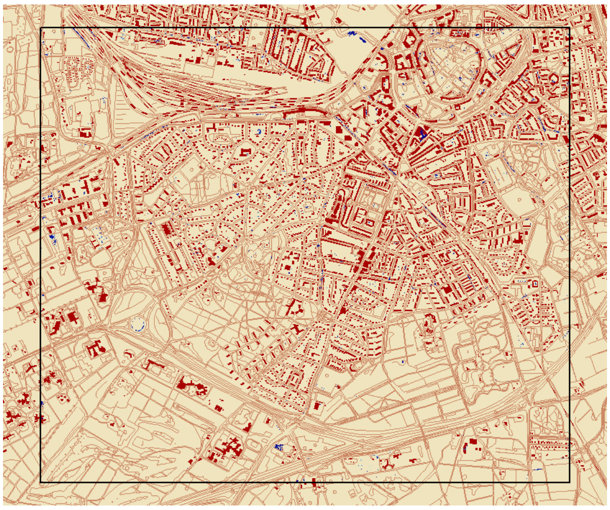
The generated inundation maps of the analysed model runs are shown below (if not depicted in chapter 5), including the output of spatially variable radar, spatially averaged radar and rain gauge.



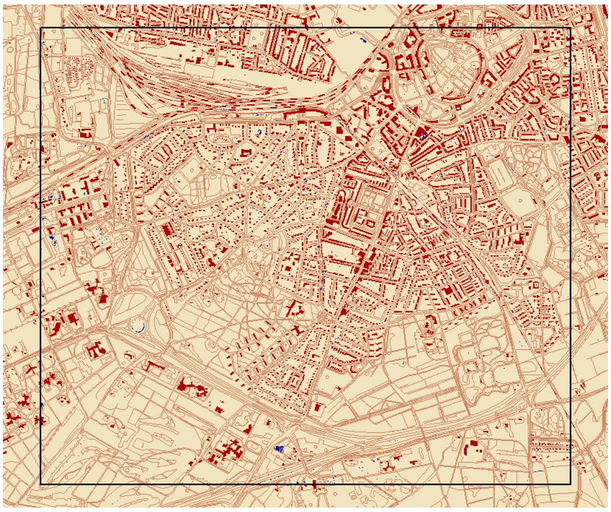
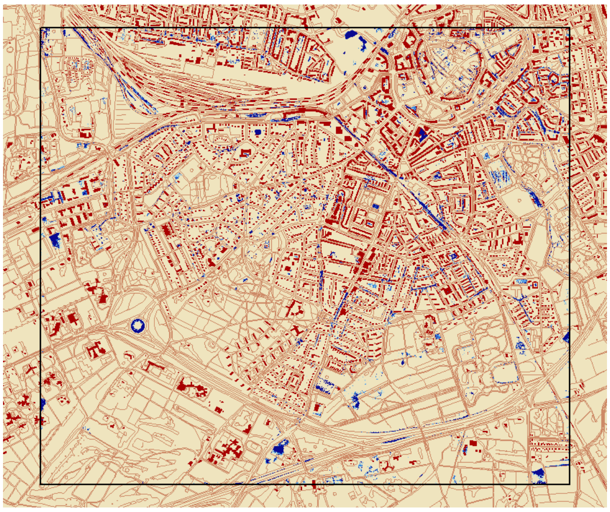
August 7, 2001. Simulated water at street (blue areas) for spatially variable radar (left) and spatially averaged radar (right). No inundation has been generated on the basis of rain gauge input.



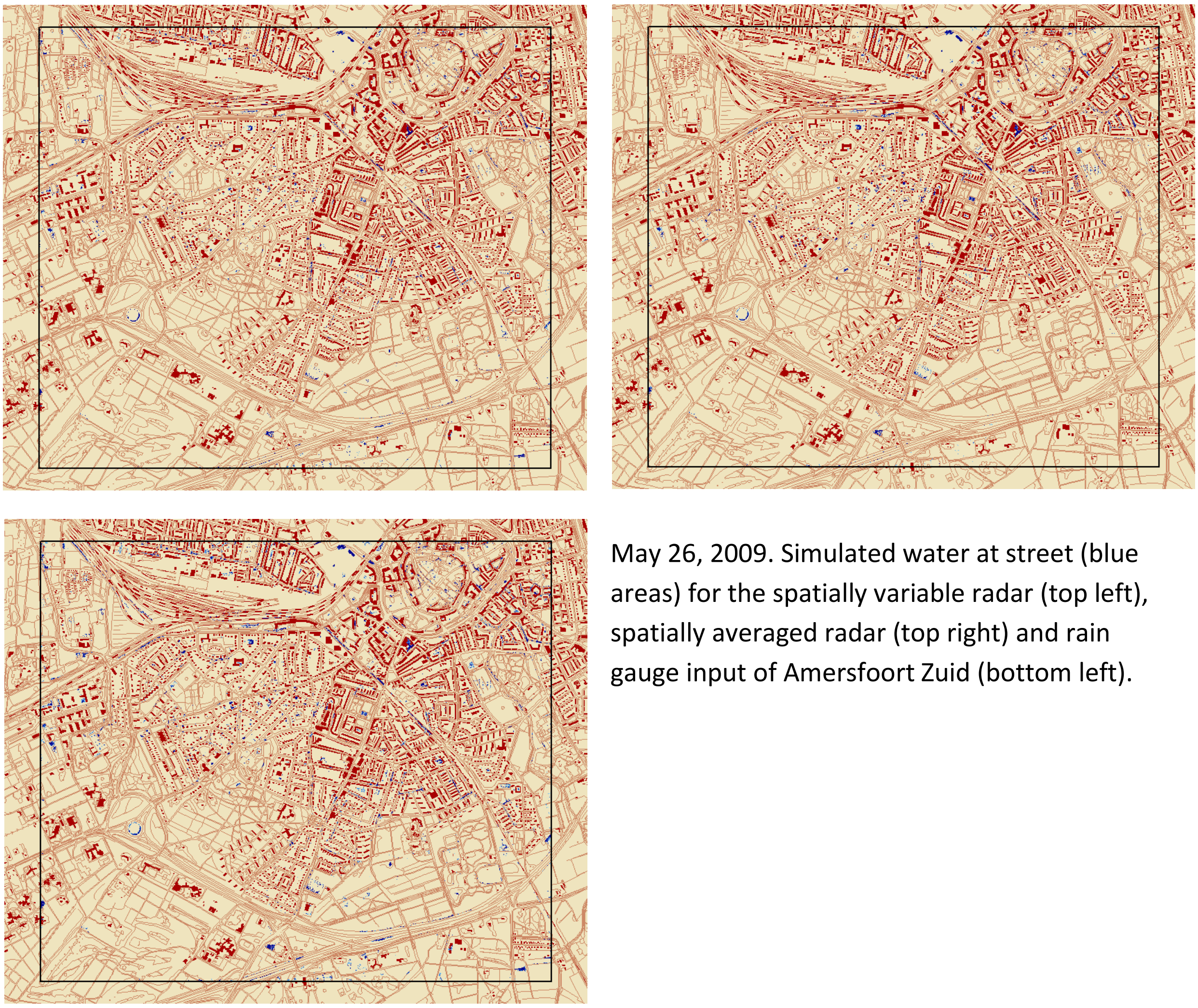
July 28, 2006. Simulated water at street (blue areas) for spatially variable radar (left) and spatially averaged radar (right). No inundation has been generated on the basis of rain gauge input.

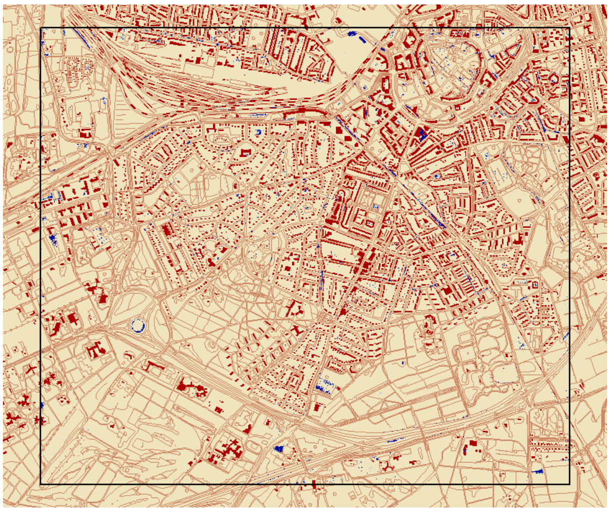
July 5, 2007. Simulated water at street (blue areas) for spatially variable radar (left) and spatially averaged radar (right). No inundation has been generated on the basis of rain gauge input.

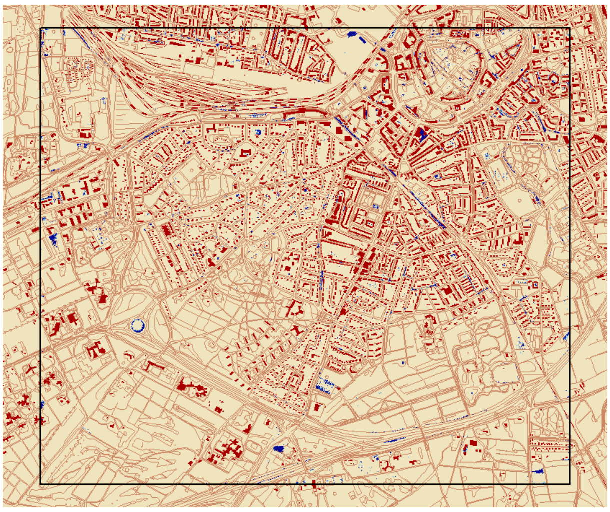




September 12, 2008. Simulated water at street (blue areas) for spatially variable radar (top left), spatially averaged radar (top right) and rain gauge Soesterberg (bottom left).

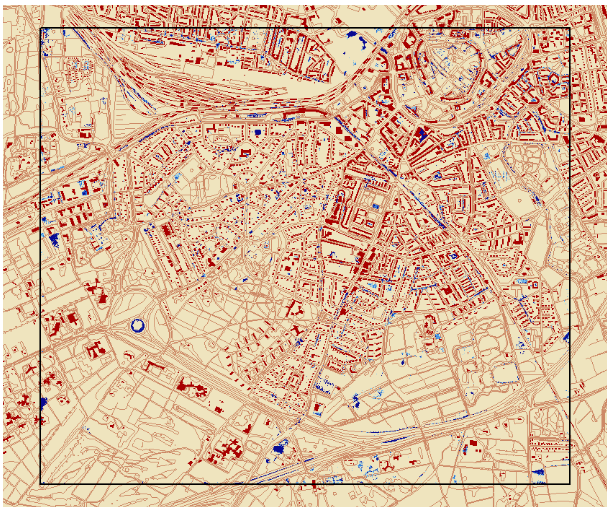


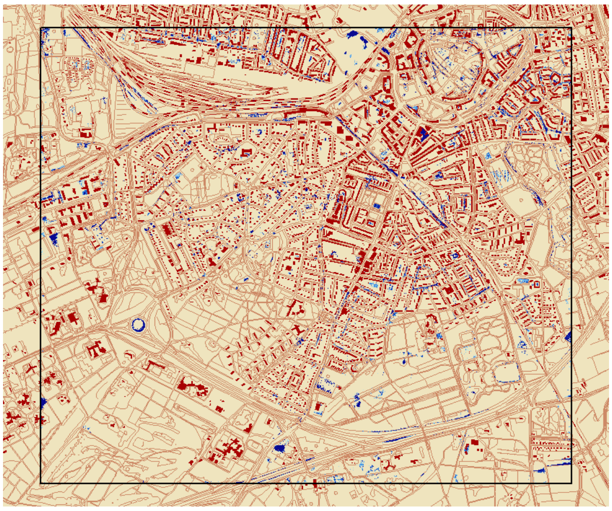
May 26, 2009. Simulated water at street (blue areas) for the spatially variable radar (top left), spatially averaged radar (top right) and rain gauge input of Amersfoort Zuid (bottom left).

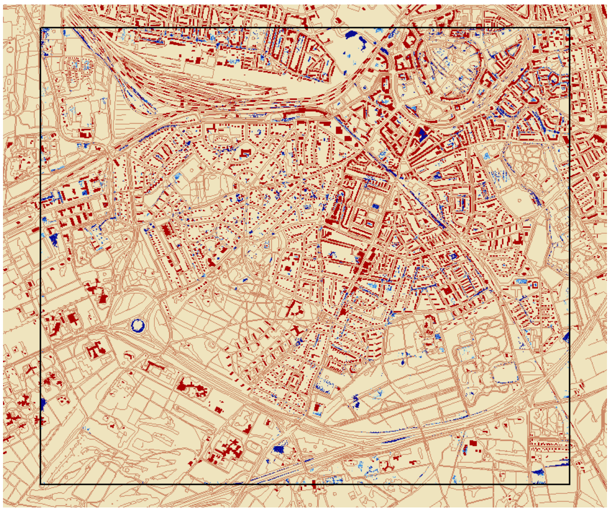




August 28, 2009. Simulated water at street (blue areas) for spatially variable radar (top left), spatially averaged radar (top right) and rain gauge input of Amersfoort Zuid (bottom left).

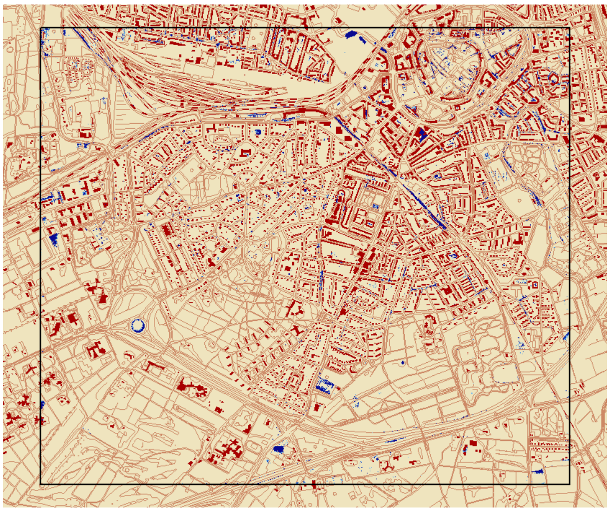


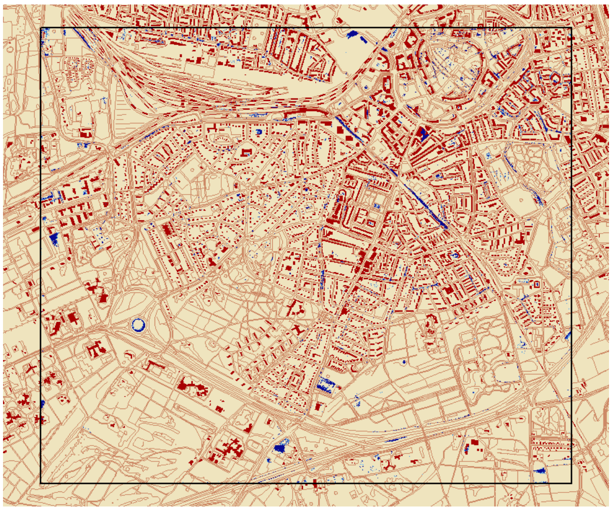


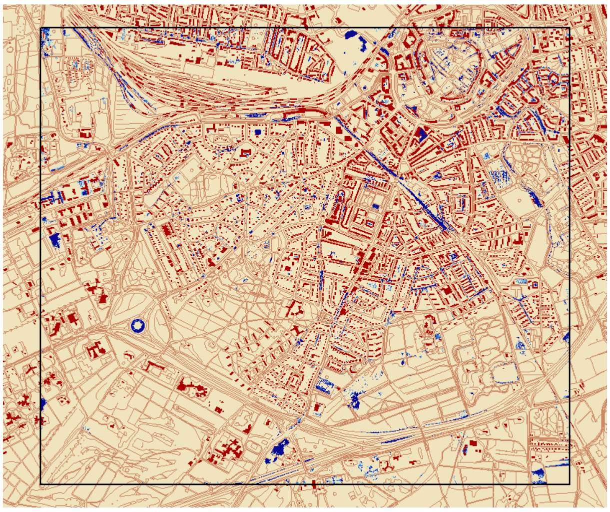


July 10, 2010. Simulated water at street (blue areas) for spatially variable radar (top left), spatially averaged radar (top right) and rain gauge input of Amersfoort Zuid (bottom left).

August 4, 2010. Simulated water at street (blue areas) for spatially variable radar (top left), spatially averaged radar (top right) and rain gauge input of Amersfoort Zuid (bottom left).







August 26, 2010. Simulated water at street (blue areas) for spatially variable radar (top left), spatially averaged radar (top right) and rain gauge input of Amersfoort Zuid (bottom left).