2009

Urban flood forecasting using high resolution radar data

AKLILU DINKNEH TEKLESADIK

MSc Thesis (WSE-HI 09-15)

UNESCO-IHE Institute for Water Education

Urban flood forecasting using high resolution radar

Application to the urban drainage network of the city of Amersfoort in the Netherlands, using a web-based information system

Master of Science Thesis

By

AKLILU DINKNEH TEKLESADIK

Supervisors

Dr.Z. Vojinovic (UNESCO-IHE)
Dr.A.H. Lobbrecht (UNESCO-IHE)
Ir.S. J. van Andel (UNESCO-IHE)

Examination committee

Chairman Prof.Dr. R.K. Price (UNESCO-IHE)

Dr ir. A.H. Lobbrecht (UNESCO-IHE)

Dr.ir. Z. Vojinovic (UNESCO-IHE)

External examiner Ir. T.S. Knippers(HydroLogic)

"The work in this report received funding from the EU 6th Framework SWITCH project (no.018530)"

This research is done for the partial fulfillment of requirements for the Master of Science degree at the UNESCO-IHE Institute for Water Education, Delft, the Netherlands

Delft

September 2009

ABSTRACT

Radar data with resolution of 1 km x 1 km grid cells measured at 5 minute interval is available from Royal Netherlands Meteorological Institute (KNMI). This data will be used to study the spatial and temporal variability of rainfall and usefulness of this data for urban drainage system modelling, where catchments have fast response for rainfall, will be evaluated.

Amersfoort is one of the big cities in the Netherlands with hilly part and flat part at the bottom of the hill. During high rainfall even some flooding and CSO occurs at the bottom of the hilly area and to solve these problems simulation model for the urban drainage system using high resolution radar rain data as input is developed. Using prediction models based on high resolution radar rain forecast data available from KNMI application of proactive real-time control system for optimal solution of flooding and CSO problems is evaluated.

An online information system presenting simulated and measured parameters in the urban drainage system through a web page using SWMM simulation model and high resolution radar data is developed.

Keywords: Proactive Real time system, high resolution radar data, rainfall variability, urban drainage system, online information system of urban drainage

ACKNOWLEDGEMENTS

Firstly, I would like to express my greatest gratitude to my supervisors Dr. Arnold Lobbrecht, Dr. Zoran Vojinovic and Schalk Jan van Andel for there vital encouragement, advice and assistant through out the thesis period.

Secondly, I would like to be grateful and extend my heartfelt gratitude to Timmy Knippers of HydroLogic for being a wonderful mentor and for his vital assistance during data collection.

I also would like to thank HydroLogic of Netherlands for giving me the opportunity to do my research in this project by coordinating the stake holders.

My sincere gratitude to my lecturers Prof. Solomatine, Prof. Price, Prof. Mynett, Dr. Ann Van Griensven, Dr. I.Popescu, Dr. A. Jonoski and Dr. Bhattacharya for their interesting and useful lectures. I am also grateful for PhD fellows in department of hydro informatics for there help and guidance.

I am thankful for the financial support from Netherlands government through NFP scholarship (Netherlands Fellowship Program).

My dear classmates you were wonderful accompany, it was really fun to study together with you guys I remember how bad we felt when class is over.

I would like to send my warmest regards for dear friends I met in the Netherlands: Davide, Linh, Chu Kai, Pato and all IHE participants. Thank you very much for making every day life very exciting in the two years journey, your accompany will be missed a lot.

Most especially to my family and good friends without their support this would have been impossible.

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

1. INTRODUCTION

1.1 Background information

Since 2008 more than 50% of the world population is living in urban areas where also most of population growth in the future is expected (Population-Reference-Bureau, 2008). This will create additional pressures on existing water supply and sanitation infrastructures. Expansion of urban areas to neighboring rural areas will change catchments into impervious surface (Gupta, 2007). This affects runoff due to decrease in flow resistance, infiltration and surface detention storage capacity of catchments. Due to these rainfall-runoff response of urban catchments is fast: surface runoff takes short time to flow into the discharging sewer system (Desa and Niemczynowicz, 1996). So heavy rain in a short period of time will overcome the capacity of the drainage system and will cause a sudden flooding as the one shown in figure 1.1.

Figure 1.1 Flooding due to excessive storm water in sewer system(Kluck et al., 2005)

In highly urbanized areas expanding the capacity of urban drainage system to accommodate peak flow from extreme events is difficult due to space and economical limitations. Many solutions are being taken by water managers to distribute peak flow over a longer time so that the available structures can accommodate the storm water without flooding. In the Netherlands experiments are going on to slow down the rainfall runoff process by planting vegetation on the roofs and expanding green park areas to increase pervious surface in urban areas (Lobbrecht and Andel, 2005). In areas where there is no space to expand green park areas and build a new sewer system it is a big challenge for the water managers to solve the flooding problems. This problem is being worsened due to climate change as extreme rain events will be frequent and this is going to affect urban areas with flood (M.Grum et al.,

2005). Therefore in this research alternatives to solve these problems will be evaluated using real time high resolution radar data and urban drainage system modelling tool.

1.2 Urban drainage systems

In order to transport the waste water from domestic households and other waste water sources construction of sewer pipes dramatically increased starting from mid 20th century. Currently urban drainage systems are of either combined or separate systems (separate pipes for storm water and waste water). Especially in old part of many cities drainage systems are partly combined and partly separate (Olofsson, 2007). During dry weather these pipes transport waste water to treatment plants effectively but during wet weather there is additional load from storm water and this causes problem in the waste water transportation. Part of the waste will be directly released to the receiving waters due to limited capacity of waste water treatment plants and/or due to limited capacity of pipes overflows could occur on streets (Ruggaber et al., 2006). In combined sewer system overflow (CSO) during excess rainfall causes pollution problems in receiving waters and in urban areas. Providing a uniform flow to treatment plants is essential for efficient operation of treatment plants but is a challenge to achieve due to variation of rainfall. In separate sewer system the storm water and waste water have separate pipes and the storm water will be directly discharged into receiving water but this may have an impact as polluted runoff from streets containing different heavy metals is discharged into receiving waters and affect aquatic life and water quality (Toffol et al., 2006). In modified separate sewer system the first flash after a rain event following a long dry period will be discharged into the waste water treatment plants while the remaining water is directly discharged into receiving waters.

1.3 Urban Drainage system Modelling

Software packages are available to simulate the behavior of a given system so that proper measures will be taken based on the simulation results. However proper care should be taken as simulation model by itself is not smart to solve the problem and the output of the model depends on many factors like how the modeller schematized the system within the model, the quality of input data used and on the calibration of the model using observed data (Price). The main objective of modelling in urban watershed is to understand how the system responds for a single or series of storm events specified by the modeller and take appropriate action accordingly (Akan, 1993). Computer based urban drainage models cover hydrologic and hydraulic aspects starting from precipitation input for each sub catchments to water depth and flow rates in pipe networks (Olofsson, 2007). SWMM (Storm Water Management Software), MOUSE (Modelling of Urban sewers), SOBEK Urban and MIKE Urban are some of the main software packages used for urban drainage system modelling. For this research SWMM is used because it is open source software, its input file is a single text file which is simple to manipulate in automated system.

1.4 Precipitation data

Precipitation is the basic input for urban sewer system simulation models so proper measurement of it is essential for the accuracy of simulation models. Rain gauges and radar are commonly used to measure precipitation; the former is a point measurement while the

latter measures spatial distribution of rain. Rain radar measurements adjusted with ground rain gage measurements are found to be far better than gage measurements as it incorporate the advantage of both radar and gage measurements (Woodley et al., 1975). Radar measures reflectivity of rain droplets and this reflectivity are converted into precipitation using a specific algorithm developed (Anagnostou and Krajewski, 1999). The technology of measuring reflectivity has limitations due to factors like attenuation and clutters so the accuracy of precipitation measured using radar depends on how much we corrected errors due to these factors. Some times this attenuations are neither excessive to be detected nor small to be neglected and this will cause a problem in the accuracy of the rain estimation (Gorgucci et al., 1996).

1.5 Setup of the thesis

In this research, using high resolution radar rain data, rainfall variability will be studied and application of this data to solve flooding and CSO problems in urban areas will be evaluated. Radar rain data is measured by Royal Netherlands Meteorological Institute (KNMI) with a 5 minute interval and 1 km x 1 km spatial resolution. HydroNet a tool developed by HydroLogic make this data available on real time (with 15 minutes lag for data processing) and this will be used to develop a demonstrator to provide online information about urban drainage system and flood forecast.

1.6 Reader

In chapter two to understand the current state of the art in urban drainage system, high resolution radar data application and real time control literature review is made. Chapter three and four explains the objectives of the thesis and the case study area respectively then methodology used to achieve the research objective is discussed in chapter five. Input data and tools used are mentioned in chapter six. In chapter seven analysis on the case study area is made and analysis results are discussed in chapter eight. Then in the final chapters conclusion and recommendations are listed.

2. LITERATURE REVIEW

2.1 RTC application in Urban Drainage

In order to address flooding and pollution problem due to CSOs structural measures increasing storage and discharge capacity of the urban drainage systems has been the main solution; however due to economical and spatial constraints plus long implementation time these structural measures are not always an efficient way of solving the problem (Ruggaber et al., 2006). Water bodies are seeking for non structural measures to optimize use of the currently available system before implementing a new structure for improved operational water management system (Geerse and Lobbrecht, 2002).

Implementation of real-time control on urban water systems will improve the operational management of the system; hence optimized use of existing infrastructure (Nelen, 1991). Controlling urban water systems in integrated manner, i.e. simultaneous and coordinated control of sewer system and treatment plant, possibly also of receiving water bodies and wastewater production units will give a better result for analyzing both qualitative and quantitative aspects of waste water as well as capability to control the environmental conditions of the receiving waters (Butler and Schütze, 2005). This will also avoid the need to build a new structure; hence the cost associated with developing new RTC system will be feasible compared to the cost of building a new infrastructure. RTC system allows redistribution of water in the drainage system and control the combined sewer overflows.

One example of RTC system is the Quebec Urban Community System where 5 moveable in-line gates controlled by Programmable Logic Controllers (PLCs) direct the combined water in real time to two underground storage tunnels with a combined storage volume of 15,000 m3. This RTC system is based on data from 17 flow monitoring and weather stations. RTC application reduced overflow volume by 70% in 2000 and only cost US$2.6 million compared to US$15.5 million which is the estimated cost of conventional structural measures to reduce the over flow in the same amount(Ruggaber et al., 2006).

In summery in RTC systems controlling process variables (water depth, flow rate etc) are monitored in the system and continuously used to operate actuators (gates, weirs or pumps) during the process. And these process variables can be determined based on forecast from process simulation using one of the available modelling softwares; then the system will be operated efficiently with best alternatives determined based on online optimization.

In the Netherlands Fleverwaard water board implements application of model prediction to control water level in Flevopolder: hydrological model is used to predict water level and the result is used for economical optimization of pumping (Hoogeveen, 1990). And this kind of system is proactive rather than reactive control as behavior of the system for dynamic loading in short future is known; it give flexibility for making the system ready to handle the situation beforehand. For the proper functioning of the RTC system quality of forecasted data is important and it should be representative both temporally and spatially in addition to accurate simulation model.

2.2 Spatial and temporal Data

Convective rains, which are responsible for most of the flooding that occur in urban areas, are limited in space and this makes spatial properties of rain essential in rainfall-runoff modelling of urban areas (Desa and Niemczynowicz, 1996). The temporal and spatial variation of precipitation is very important for surface and sub surface flows in catchments as these estimates are very essential for hydrological models estimating soil moisture and ultimately for flood forecast. Rain gage stations will provide better estimate of rain at a single point but in case of poor rain gage network because only few point measurements are available, grid cell averaged radar estimates can provide a more accurate spatial distribution of precipitation and this leads to a better calibration of rainfall-runoff based models (Lobbrecht and Andel, 2005). Urban areas require very large spatial and temporal resolution of rain data and to achieve this high resolution using rain gage needs a very dense network of gages which is very difficult to build and maintain both from financial and practical point of view (Bernea et al., 2004).

2.3 Weather Radar

2.3.1 What is Radar

Radio Detection and Ranging (Radar) has been used for estimation of precipitation since the existence of radar meteorology. Radar provides high spatial resolution precipitation data that can be used in urban drainage modelling (Vieux et al., 2005). In general weather radar has a wide application ranging from disaster prevention, flood and drought monitoring, to agricultural and municipal water usage issues. Weather radar has better temporal and spatial resolution compared to rain gauge, where point measurements at different stations are interpolated to get the rainfall over large area, but the latter is used to get the ground truth for rainfall totals in the vicinity of the gauge.

2.3.2 Components of Radar

Radar has four basic components:

- A transmitter, which creates the energy pulse.
- A transmit/receive switch that tells the antenna when to transmit and when to receive the pulses.
- An antenna to send pulses out into the atmosphere and receive back reflected pulse.
- A receiver, which detects, amplifies and transforms the received signals.

Figure 2.1 depicts these four basic components of radar together with a display unit. Radar output generally comes in two forms: reflectivity and velocity. Reflectivity is a measure of how much precipitation exists in a particular area. Velocity is a measure of the speed and direction of the precipitation toward or away from the radar. Most radar can measure reflectivity but you need a Doppler radar to measure velocity.

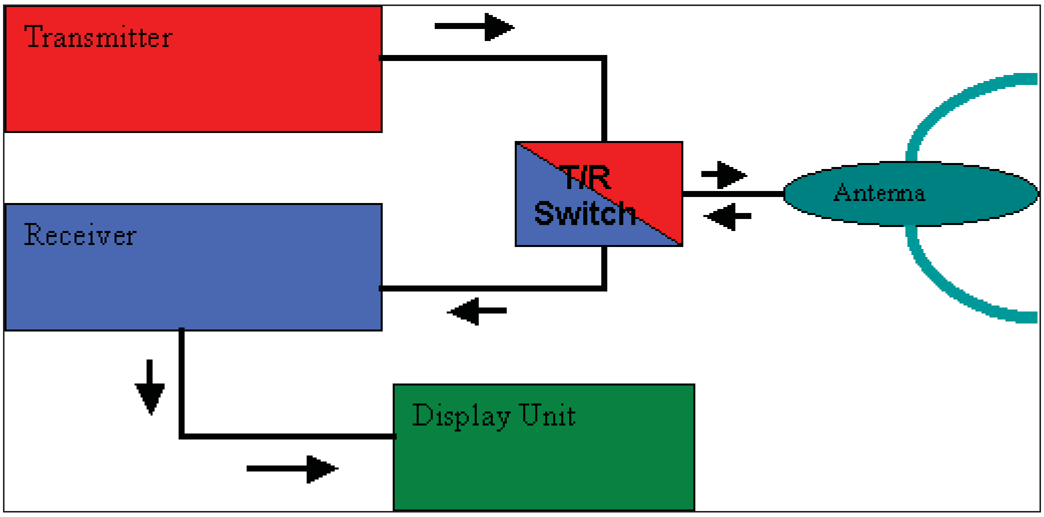


Figure 2.1 Components of radar

2.3.3 Working Principle of radar

In 1886 Heinrich Rudolf Hertz in Germany detected that an electric current swinging with speed of light back and forth in a conducting wire would radiate electromagnetic waves into the surrounding space (today we would call such a wire an "antenna"). In the following decades these properties were used to determine the height of the reflecting layers in the upper atmosphere. This is why data received from the radar is called reflectivity (Australia-Bureau-of-Meteorology, 2009).

1842 the Austrian physicist Christian Doppler discovered the theory that sound waves will change in pitch when there is a shift in frequency what is now called the Doppler Effect. This theory is used by Doppler weather radar to determine the speed of precipitation in the atmosphere and generally when precipitation fall moves with wind, wind velocity can be determined with Doppler technology.

Transmitter of radar spreads a wave of electromagnetic energy (pulse) and this energy scatters in all directions out of which a very small portion is reflected back from the target (raindrop).

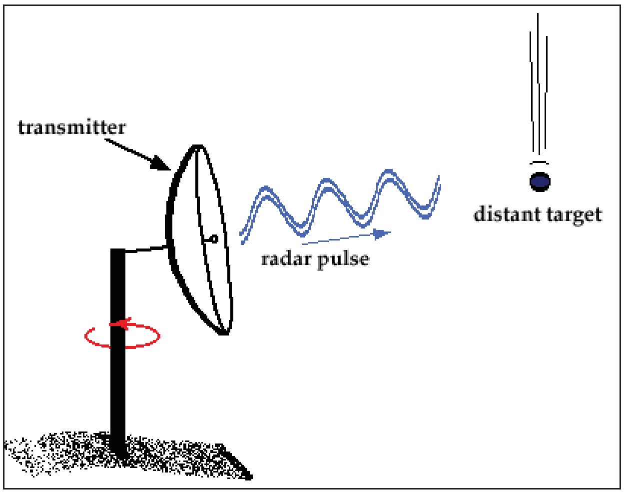


Figure 2.2 Radar pulse scatter from the transmitter(Kane, 2004)

Collectively, energy is scattered back to the radar from millions of droplets to generate the radar reflectivity.

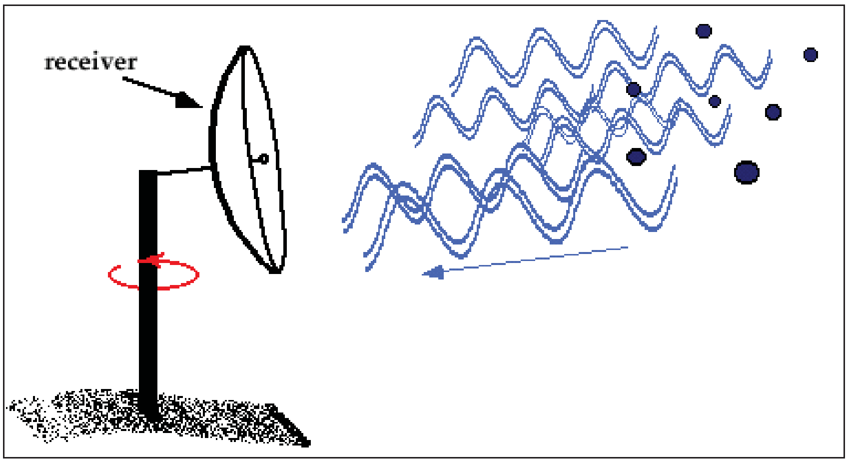


Figure 2.3 Radar pulse reflecting back from rain droplet to receiver(Kane, 2004)

The strength of the pulse returned to the radar depends on the particles size, number and state (solid-hail, liquid-rain). After making many assumptions about these factors and others, the approximate rain rate at the ground can be estimated. In fact, the most reflective precipitation particles in the atmosphere are large and usually have a liquid surface (water-coated hailstones).

In the Netherlands KNMI (Koninklijk Nederlands Meteorologisch Instituut) uses two radar stations at De bilt and Den helder (shown in figure 2.4) for measuring precipitation with 5 minutes time step and 1kmx1km spatial resolution.

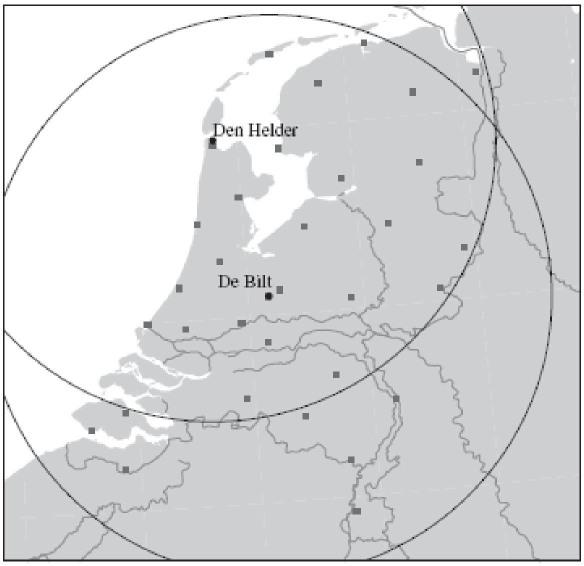


Figure 2.4 Coverage of two radars in the Netherland (Holleman, 2009)

Radar transmits a focused high-power beam of radiation and receives a meager amount of radiation back from whatever the beam encounters. Reflectivity, which is a measure of how much power is scattered back to the radar from any target, is interpreted to precipitation based on different algorithms. Weather radars are classified into different bands based on the radar frequency used. C, S and L are low frequency bands used for precipitation measurement while W, K and X are high frequency bands used for cloud detection. LAWR (Local area

weather radar) developed by DHI for rainfall forecast within 60 km radius use x-band radar which has short wave length of around 3 cm (DHI). A radar dome and its section view are shown in figure 2.5.

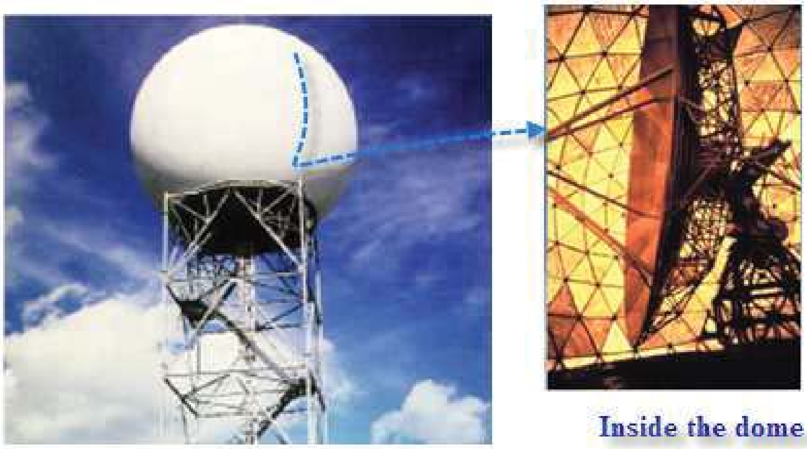


Figure 2.5 Typical Doppler weather radar

These C-band radars emit and receive radio-waves with frequency of about 6GHz and wavelength close to 5cm (Holleman, 2009). The received signals, after calibration and correction for distance, will be converted into reflectivity (Z) and this reflectivity will further be corrected for cluttering and attenuation effect before converting it to rainfall.

The Constant Altitude Plan Position Indicator (CAPPI) is a radar display which gives a horizontal cross-section of data at constant altitude. The CAPPI is composed of data from each angle that is at the height requested for the cross-section (bold lines in zigzag on the figure 2.6).

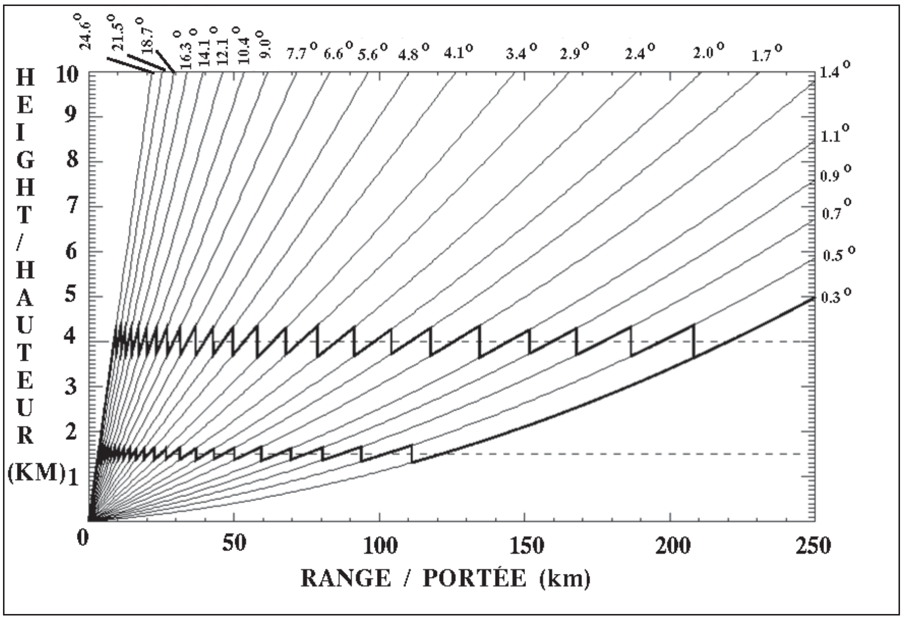


Figure 2.6 Constant Altitude Plan Position Indicator at a height of 1.6 km and 4 km

Figure 2.7 shows map for reflectivity measured above the Netherlands for an event on 8th of August 1999, 16:34 UTC for 0.8km CAPPI.

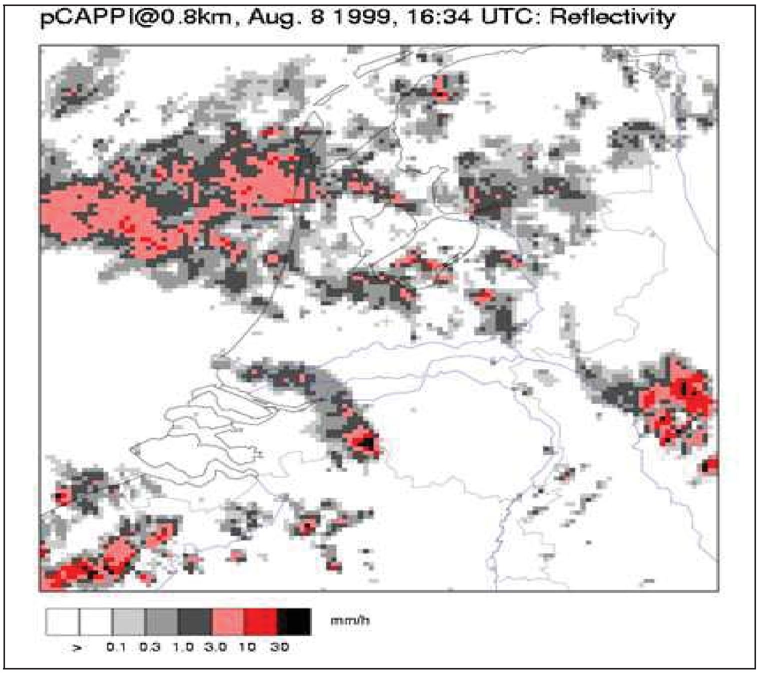


Figure 2.7 Map showing reflectivity. (Holleman, 2009)

So weather radars measure the reflectivity of the surface area of the rain droplets at certain height CAPPI while rain gauge measures the volume of rain. A lot of researches have been carried out in 1970s and 1980s to develop an algorithm for converting this reflectivity into rainfall volume (Steiner et al., 2004) And most of these researches produce this relationship

$$Z = a * R^b$$

Where:

Z is reflectivity in (mm^6/m^3)

R is rainfall rate in (mm/hr) and

a and b are empirical coefficients.

The value of these coefficients depends on the drop size distribution of rainfall: as the drop size distribution changes so do these coefficients.

KNMI uses the following formula to convert the radar reflectivity into precipitation:

$$Z[mm^6/m^3] = 200 * R[mm/h]^{1.6} \qquad \text{(Holleman, 2009)}$$

Or when Z is expressed in decibel-unit

$$Z[dBZ] = 23 + 16\log_{10} R[mm/h]$$

Z-R relationship varies in space and time due to the spatio-temporal variation of the rain drop size but this variation can be calculated from the average value for a certain event and assuming the Z-R is constant with in the storm Estimation of the mean Z-R in real time is difficult so this value is estimated based on average over several events. Different methods are being used by meteorologists to correct these effects but still calibration using data from point measurement is essential.

2.3.4 Error in Radar

Despite continued development and improvement in estimation methods of radar rain it is widely acknowledged that errors in the rainfall estimates still exist (M.P.Mittermaier, 2008). A lot of researches have been carried out to improve the accuracy of weather radars by trying to eliminate the errors such as anomalous propagation, partial beam filling and bright banding either by developing a method which adjust radar estimates of precipitations for these error sources or adjust the radar precipitation estimates based on in situ rain gauge data. But other problems still remain: for example radar may underestimate precipitation because the droplet size of light rain drops is too small below the detection size (M.P.Mittermaier, 2008). In some cases radar may simply not be able to see all the precipitation, due to the partial blocking or the beam overshooting. Other limitations of radar technology include attenuation which is scattering and absorption of beam energy and reflection from ground structures, airplanes or other flying objects. The location of the radar is also very important to catch clouds at all range of altitudes with in the radius of the radar coverage as otherwise radar may miss some clouds at lower altitude.

2.3.5 Calibration of radar data

For the study area 1km x 1km resolution radar precipitation data with 5minutes time step is available from KNMI and this data is calibrated using point measurements on ground stations. KNMI uses precipitation data from 33 rain gauge stations throughout the Netherlands to calibrate the radar precipitation measured by two radar stations at De bilt and Den helder (shown in figure 2.1). For some areas it is very difficult to find a specific Z-R relationship due to the nature of the rain so calibrating radar rain with data from denser gauge networks is important for better estimation of rain.

2.4 Weather Forecast

Shortage of rainfall has an impact on availability of water for domestic, agricultural and industrial purposes; if it is in excess it can cause floods and flash floods so reliable weather forecast of precipitation is of vital important for successful management and operation of related infrastructures. Rainfall forecast skills are improved with the invention of new instruments like radar and satellites together with increasingly complex numerical models and high performance computers (Grecu and Krajewski, 2000).

Using these available methods it is easy to forecast intense events better than weak events (Grecu and Krajewski, 2000) and in the same study the author showed that better forecast, with a correlation coefficient between measured and forecasted rainfall data above 0.5, was observed from numerical prediction models with a lead time (how far in advance) of 30 minutes. Flood forecasting can be improved by integrating short term radar nowcasting (forecast with short lead time) and numerical model predictions.

KNMI provides forecasts of rain with a 1km grid and 5 minutes interval for 2 hours lead time and the first hour forecast was already found to be within a reasonable accuracy where the forecast for more than1 hour lead time still needs further analysis.

2.5 Decision Support System in Urban Water Management

Water managers have to decide how to handle the excess water during rain event in such a way that there will be no flooding on streets or environmental damage due to pollution from combined sewer overflows. In the Netherlands water managers in municipalities together with water boards hold these responsibilities and they are making effort to decrease storm water flow into treatment plants by maximizing infiltration and retention locally (Kluck et al., 2005). Information about quality and quantity of water in excess of the urban drainage system capacity will have important role in sustainable urban drainage system management. Using available rain nowcast and running simulation model using this data the behavior of the system for expected rain will enable water managers for a better management of the system.

In urban drainage system predictive modelling to determine flow characteristics in the pipe networks using distributed rain prediction have been suggested as possible approach in providing better information and already implemented in 1999 in RHINOS (Real-time urban Hydrological Infrastructure and Output modelling Strategy) (Yuana et al., 1999).

A lot of researches have been done in the area of decision support system for urban drainage application. These DSS, at least in the Netherlands, are mostly limited in providing information about current situation with in the drainage system and in some cases weather forecast will be used to make the system ready for an expected rain by emptying storages so that enough capacity will be there to accommodate upcoming storm water.

In Fleverwaard water board for example prediction models are used for RTC application but this is using the advantage that polders have slow response for rain to produce runoff. Here hydrological models are used to predict water level in canals: after each rain event based on prediction of discharge from polders (and then water level in canals) by the hydrological model pump operations will be optimized by a RTC system to control water level.

In the United States embedded sewer network sensors are used to maximize the storage capacity of UDS by distributing water in the system hence reducing CSO and flood based on real time measurements with in the drainage system (Ruggaber et al., 2006). But the application of prediction model using rainfall forecast is not that much studied so far.

In this research using high resolution radar rain data a web based information system will be developed and application of proactive RTC system for solving CSO and Flooding problem using model prediction will be evaluated.

3. OBJECTIVES

General objectives of urban water management are: to reduce urban flooding problems, to make efficient use of treatment plants, to minimize pollution due to combined sewer overflows and to meet receiving waters quality requirements. These objectives may not be supportive to each other so trying to achieve one objective independently will lead to worsening the others. Integrated management of the urban water system is essential in order to achieve these objectives in a best way. In modelling of urban water systems the big challenge is the availability of sufficient representative data, both temporally and spatially. High resolution radar data will give better representation for spatial variation of rainfall, and in this research spatial and temporal variability of rain will be evaluated using the high resolution radar data available to show the benefit of this data for urban water system modelling.

Providing adequate information about the current performance of the drainage system for decision makers and operational managers is important for controlling the system in a better way and if information is available about how the system is going to react for a forecasted rain event it will make decision makers capable of taking proactive measures to utilize the system in a better way and avoid flooding which could have occurred due to insufficient utilization of the system.

Designing sewer systems in urban areas for the extreme events with large return period may not be economical so we have to look for alternatives and in this research possible application of RTC for efficient use of the system will be evaluated.

To achieve research objectives a case study was conducted in the city of Amersfoort, which is one of the big cities in the Netherlands.

The objectives of this research can be summarized as follows:

- To develop a demonstrator for real time modelling of urban water system using high resolution radar data.

  High resolution radar data will be used to run an online simulation model of the urban water system and the results of the model will be published on a website together with real time measurements for the public access.

- To study variability of rainfall using high resolution radar data available and hence evaluate advantage of using these data for urban flood modelling applications.

  Urban areas are very sensitive for spatial variation of rainfall in the catchments of the sewer system and approximations of point measurements using rain gauges into the sub-catchments will underestimate or overestimate the spatial variation. Radar rainfall data presumably gives a better estimate of spatial variation and here variation of radar data with 1km x 1km grid and 5 minutes time will be evaluated.

- To reduce flooding on street and CSOs problems in the city of Amersfoort.

  Due to the topography of the city with a hilly higher part and a lower flat part flooding on streets and CSOs occur. Different alternatives will be evaluated to reduce flooding and CSO problems. Rain radar forecasts may be used for better performance

of the sewer system in case of heavy rainfall and better distribution of sewer water over the entire sewer system.

- To evaluate if a proactive real-time control application in Amersfoort urban water system can be beneficial using new regulation structures (weirs and gates) for efficient flood management.

Urban water systems are designed for a certain rainfall event as it is not economical to design big structures to accommodate bigger rain events with higher return periods. Application of real-time control systems based on forecasts from process simulation and online optimization will increase the efficiency of the urban water system. Forecast from the radar will be used as an input for the process simulation model.

4. STUDY AREA

With over 130,000 citizens Amersfoort is one of the 20 largest cities in the Netherlands. It is a versatile city with a variety of architecture, history, art, culture and nature. Figure 4.1 shows facilities available to carry out proper sanitation of the city.

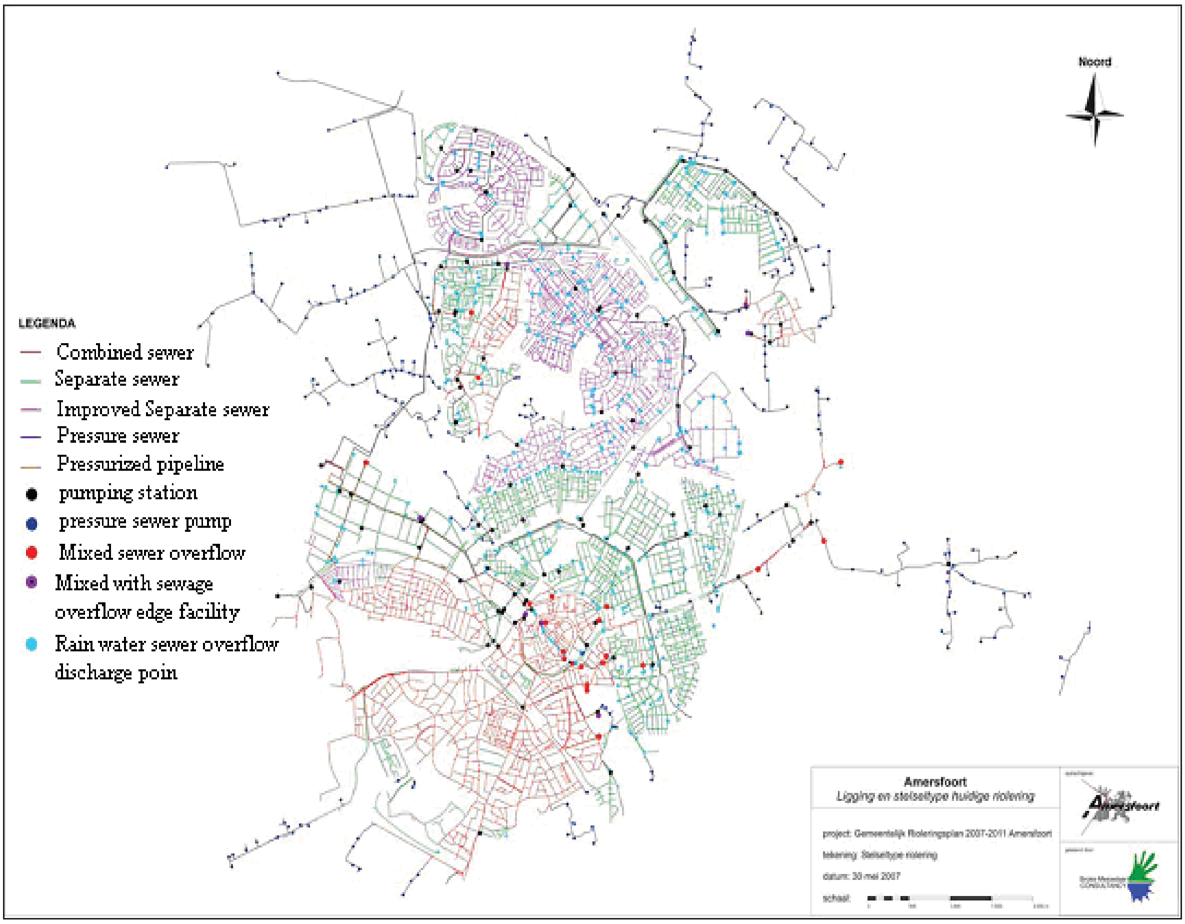


Figure 4.1Facilities in Amersfoort city for sanitation (Gemeente-Amersfoort, 2008)

The total length of this sewer network in ownership and management of the town is 878 km of which

- 156 km mixed(combined) system,
- 343 km (improved) separate rainwater system, with over 2 ½ km sewer infiltration,
- 279 km (improved) separated sewage water system and
- 62 km pressure sewerage pipe system.

Out of all Drainage system in the city 20% is combined system while the remaining 80% is a separate system. Most of the pipes in the drainage system (approximately 685 km) are made of concrete, 185km out of PVC and the remaining small portion from other materials. The size of the pipes in the drainage system ranges from as small as only 5cm to large pipes of 2.5 and 3m diameter while three quarter of the pipes are between size of 20 and 40cm.

Amersfoort city has a hilly area as shown in figure 4.2 and lower flat area; during big rain event there is flooding (water-on-street) problem on some streets located at bottom of the hilly area and CSOs.

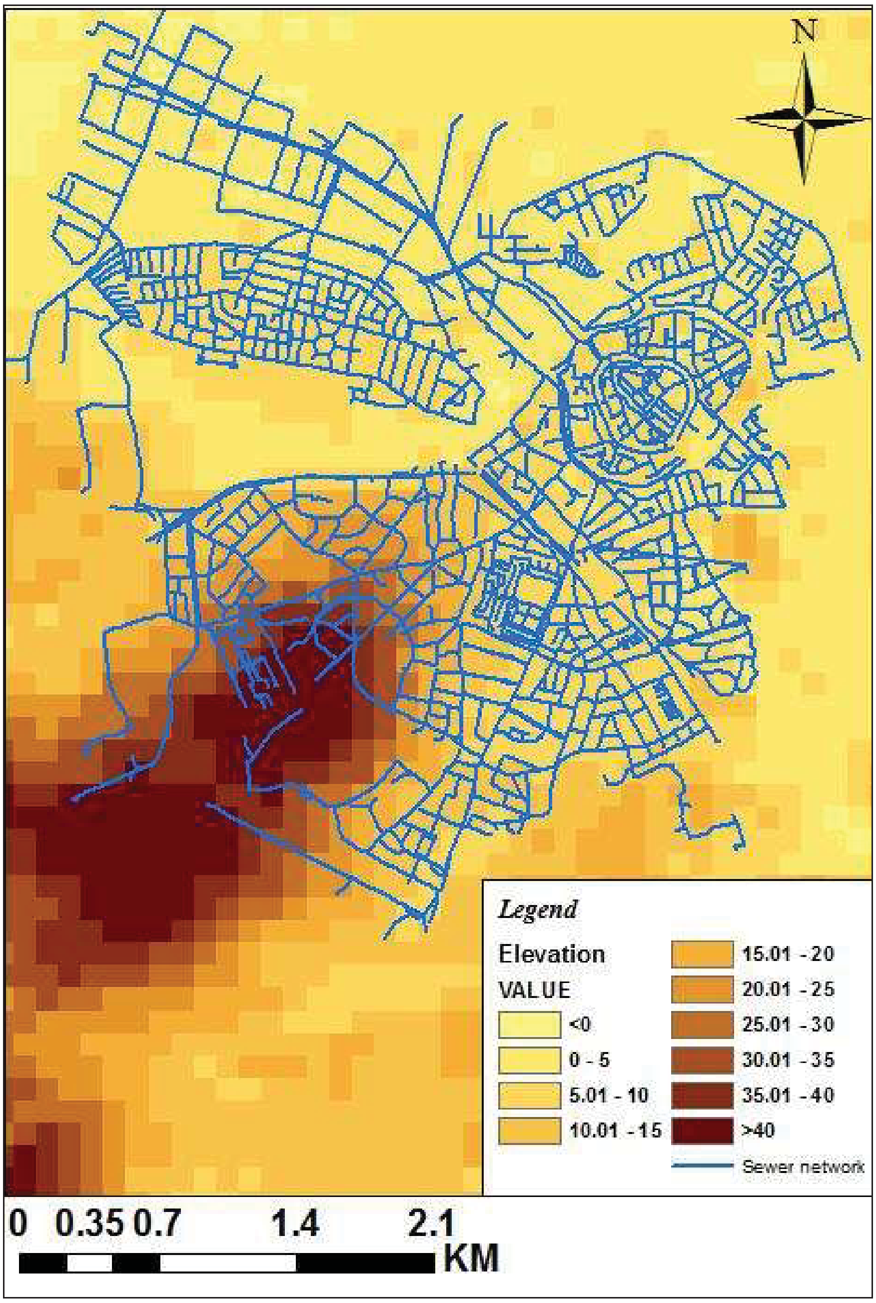


Figure 4.2 Sewer Network of the city of Amersfoort together with Digital elevation map showing the elevation difference in different parts of the city

For the case study the hilly part and flat area below the hilly part will be studied by including sewer pipe networks in these areas in a model in order to solve flooding and CSO problems which occur during high rain events in the flat part. Figure 4.3 shows a flood (water on street) after a big rain event in August 2006. The drainage system in these parts of the city is mostly combined sewer system.

Figure 4.3 Water on street due to rain event in august 2006

The same model developed for solving flooding and CSO problems will be used for evaluating proactive RTC system, which is a system that uses forecasted high resolution radar rain data available from KNMI and run SWMM model online for solving expected flooding problems. So the model is simplified by including only pipe network up to the city centre and also from this part only main pipes with bigger diameter are considered as otherwise running the model online may take long and forecasted rain event may occur before the proactive RTC system prepares the drainage system to accommodate a possible flooding.

5. METHODOLOGY

5.1 Data collection

Five minute radar rain data with 1 km x 1 km spatial resolution is available online on HydroNET urban since January 2009. This data for a period of four months is downloaded using HydroNET tool.

Rain gage data from four gage stations in Amersfoort city and three other gage stations located at De-bilt, Arnhem and Cabew for the year 2008 and January to May of 2009 is collected.

System characteristics data for the urban drainage system of Amersfoort city is collected from kiker data base and from SOBEK model of urban drainage system for Amersfoort city developed by DHV

5.2 Rainfall Variability Study

Using The 5 minute radar data and rain gage data rainfall variability will be studied. Scatter plot, coefficient of correlation and coefficient of determination will be used to compare data sets at different location and different time step of measurement. Data sets at time t and t+1 will be compared to study the variability of rain fall with time.

5.3 Modelling

Model for the urban drainage system of Amersfoort city will be developed in SWMM software package using design storm and system characteristics data.

Result of SWMM and SOBEK model will be compared to verify the SWMM model as sufficient data for calibrating SWMM model is not available.

5.4 Flooding and CSO problem Analysis

Using design storm the SWMM model will be analyzed and different alternatives like distributing the storm water in the system using control weirs and gates upstream of flooded area or using pumps if the system have unused capacity and building additional storage if capacity is fully utilized during peak flow will be evaluated to solve the expected flooding and CSO problem at the bottom of the hilly area.

5.5 Online SWMM modelling

Based on the location of the sub-catchments in the SWMM model rainfall data from 1 km x 1 km radar grid cells will be used for Online SWMM modelling. This input data is real time data and for accessing the data and running the SWMM model online with the updated data automatically a code will be developed using Visual Basic and will be implemented in the window schedule.

5.6 Building the Demonstrator

A demonstrator which present results of automatic SWMM simulation based on real time data will be developed. After running the model in the online SWMM modelling part result will be saved in a report file. A code will be developed to read data for selected nodes from this report files and prepare XML files. Then these results will be presented in a web page where real time and forecasted rainfall data together with simulation results from SWMM model will be presented. HTML and PHP coding will be used to design the web pages; to prepare the graphs from the XML files fusion flash dynamic graph plotter will be used.

5.7 Evaluation of Proactive RTC system

To solve flooding and CSO problems in the city of Amersfoort possible application of RTC system using prediction model will be evaluated. The urban drainage system will be checked for pipe capacity utilization in the system at peak flooding hour and alternative like redistributing water in the system using control gates or implementing additional storage tanks together with proactive RTC system for operational optimization will be evaluated.

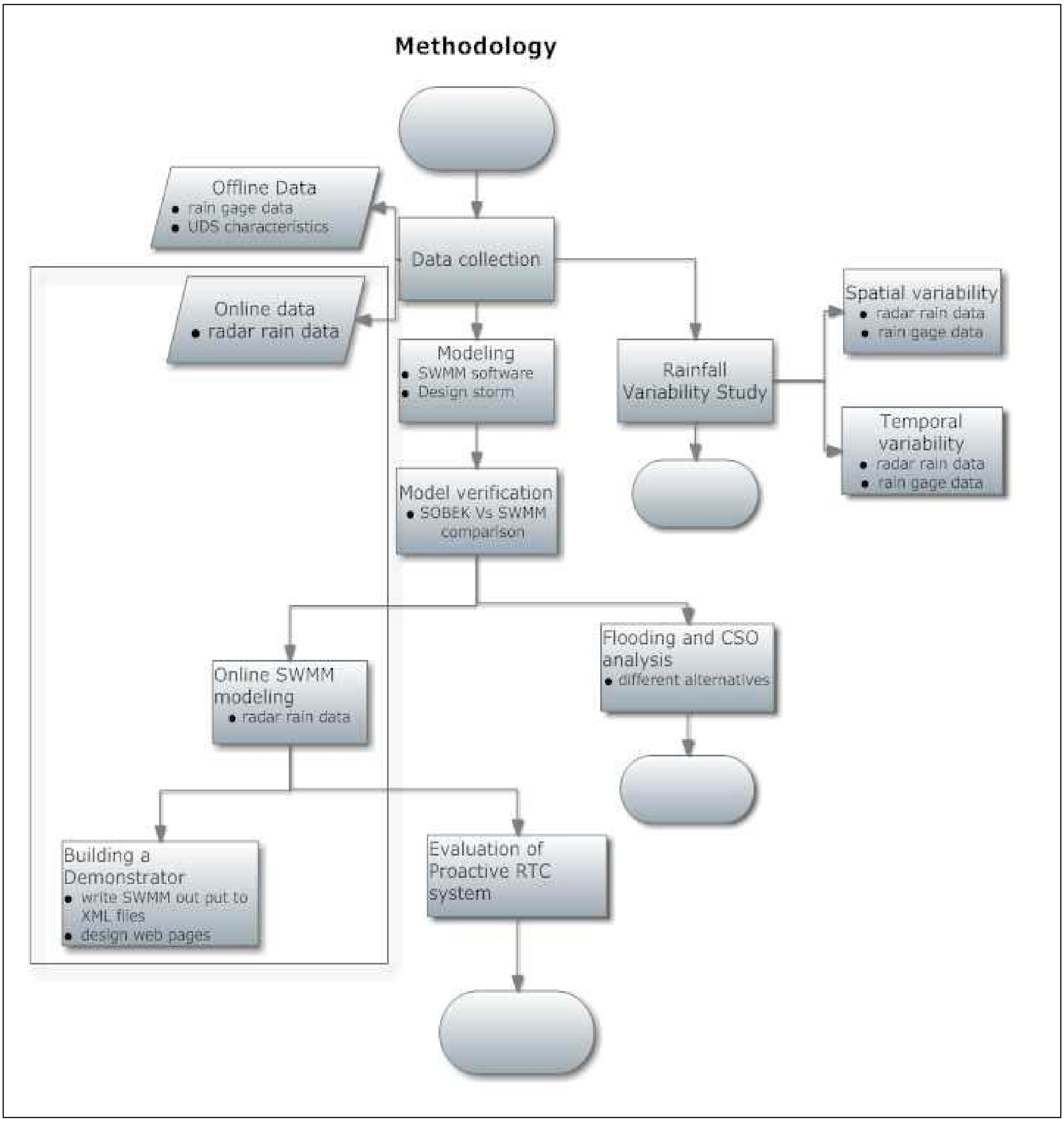


Figure 5.1 Flow chart summarizing the methodology.

In the flow chart of figure 5.1 the methodology is summarized and the rectangular block containing tasks online data collection, online SWMM modelling and building the demonstrator will be further explained in detail in chapter 7.

6. INPUT DATA AND TOOLS USED

6.1 Input data

6.1.1 Metrological Data

Radar precipitation estimates utilized in this study were made available by KNMI. KNMI operates two ground-based C-band radars, located at Den Helder and De Bilt, which are used for measurements of precipitation over the Netherlands and the surrounding area. These C-band radars emit and receive radio-waves with frequency of about 6GHz and wavelength close to 5 cm (KNMI website). The received signals, after calibration and correction for distance, will be converted into reflectivity (Z) and this reflectivity will further be corrected for cluttering and attenuation effect before converting it to rainfall.

These precipitation data have a spatial resolution of 1 km x 1 km and temporal resolution of 5 minutes. In Amersfoort there are 6 new rain gauge stations which started functioning from January 2009. Data from these rain gauges is used to compare the accuracy of the radar precipitation with respect to gauges in each grid cell.

Design storm which will be used to solve flooding and CSO problem is taken from the analysis made by RIONED. A two year design storm with peak values at the beginning of the rain event (RIONED, 2008).

6.1.2 Drainage system characteristics

Kikker (a database with all the drainage networks of Amersfoort city) is used for developing the drainage simulation model. In addition there is an existing SOBEK model developed by DHV for urban drainage system of city of Amersfoort. This model is used to cross check some unclear information in the database and other input parameters for the SWMM model which are not available in the database.

6.1.3 Hydrological data

For the urban drainage network system there are measuring stations and at these stations data like water level, pumping duration, CSO and also at some of the stations rainfall is measured. Mostly the water level measured are before a weir structure or within storage facilities and it is difficult to relay only on this data for calibration of urban drainage system simulation model. A data base with measurement from stations in city of Amersfoort was collected from ROVA but it was not easy to get drawings which indicate where exactly are these measurements being taken except for one station. Measurements from this station are used for cross checking the performance of the simulation model as it is difficult to calibrate the model using only this information at one location.

6.2 Tools Used

6.2.1 HydroNET

For pre-processing of the metrological data HydroNET (tool developed by HydroLogic in The Netherland) is used. This tool accesses radar rain data with 1kmx1km spatial resolution measured every 5 minutes from KNMI server in HDF5 format with non orthogonal grids,

converts it into orthogonal grids and calibrates it using data from gauge stations. Time series of this processed data is available through HydroNET Urban; the different water boards in the Netherlands use this tool to get time series of precipitation in the sub catchments of their interest.

For this research a code which accesses the web services of HydroNET is developed to prepare time series for each 1km square grid.

6.2.2 Data processing

GIS is used for processing data imported from the SOBEK model then the data is exported to Excel where by putting together all additional information input file for SWMM is created and saved in a text file. To bring together the different components for the SWMM input file Visual Basic is used. Figure 6.1 below summarizes the tools used in data preparation.

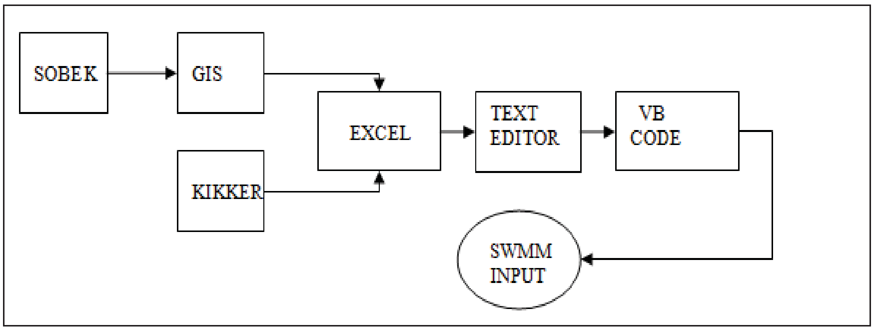


Figure 6.1 Diagram showing tools used in data processing

6.2.3 SWMM modelling software

The simulation model for the urban drainage system is developed using SWMM. In SWMM there are two options to run a model: user interface SWMM and command line SWMM. User interface SWMM is used to setup a model and see lay out of the different parameters in the model. After building the model it can be run either from the user interface or from the command line where in the former case the results can be seen on the user interface with different charts and in the latter case a report file will be generated in text format with pre selected results by the user. In this thesis both User interface SWMM and command line SWMM are used. SWMM engine takes small computation time and its input file can be prepared in a text editor, which make it simple to change input parameters for an automated run, compared with that of SOBEK input file. On top of the above reason SWMM is free software while SOBEK is commercial so it will be interesting to see how it performs in comparison with commercial software.

6.3 Tools for Web page design and presentation

For web page design and development HTML and PHP coding languages are used in Adobe Dreamweaver (CS4). XAMPP software package which includes Apache friends server, PHP engine and MySQL is used on the server computer to make the web pages globally accessible through internet browsers. For plotting graphs dynamically software called fusion chart is used where data in xml format is plotted in flash player.

7. ANALYSIS

First analysis will be made on the 5 minute radar data with 1 km x 1 km spatial resolution. Regression analysis to compare time series of data from different radar grids will be made to evaluate the relationship between grids at different distance. Radar data will be compared with point measurements from ground stations and to study the temporal variability of rain analysis will be made between consecutive data sets.

In the urban drainage system two types of analysis will be made using SWMM modelling software: offline analysis using design storm rain data for solving flooding and CSO problems and online analysis using real time radar rain data for building the demonstrator and evaluating application of proactive RTC system for Amersfoort urban drainage network. For both analyses the first step is to build the urban drainage system model using system characteristics data and then load the model for both cases accordingly. Basically there are two loadings: dry weather flow (DWF) which is waste generated from each housing unit and wet weather flow (WWF) which is loading on urban drainage system from storm water. Next tasks involved in this research and explained briefly above will be discussed in detail.

7.1 Rainfall variability

Four month (from March to June 2009) radar data of 5 minutes interval will be used for variability analysis. The type of analysis which will be made includes

- Time series analysis
- Peak events comparisons in time series
- Correlation coefficients among data sets of different grids to study the spatial variability
- Correlation coefficients between consecutive data sets in the same grid to study the temporal variability.

7.2 SWMM modelling

7.2.1 SWMM modelling software

After the input variables are determined then next step is to build simulation model and load these input variables to see how the system behaves. Both offline SWMM model to solve flooding and CSO problems and online SWMM model for the demonstrator and proactive RTC system will have the same model parameters except that the input data and the way to run the model is different. So in this part how the model is built will be explained. The wet weather flow part is going to be calculated from routing the rain fall on the sub catchments and this is done by the overland flow component of the model.

7.2.1.1 Overland flow

In SWMM the runoff model converts the excess rainfall, which is the rainfall or snow melt less the infiltration and evaporation, into runoff; this process can be simply described as in figure 6.1. As can be seen from figure6.1 sub-catchments are subdivided into three subareas

that simulate impervious areas, with and without depression (detention) storage, and pervious areas (with depression storage). These are areas A1, A3, and A2 respectively on figure 7.1.

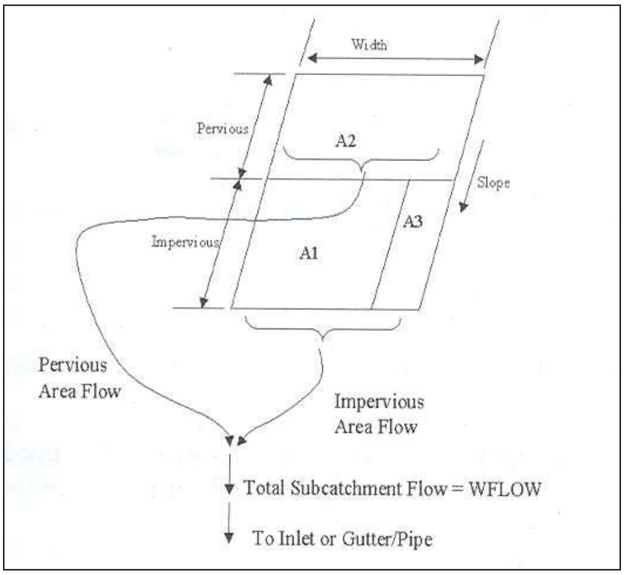


Figure 7.1 Sub catchment schematization for overland flow calculation (James et al., 2008)

Overland flow is generated from each of the three subareas by approximating them as non-linear reservoirs, as sketched in figure 6.2. This is a spatially "lumped" configuration and really assumes no special shape; however, if the sub-catchment width, W, is assumed to represent a true prototype width of overland flow, then the reservoir will behave as a rectangular catchment, as the one in figure 7.2. In modelling sewer system of Amersfoort the width, slope and roughness are considered as a calibration parameter to adjust the measured and simulated discharge hydrographs.

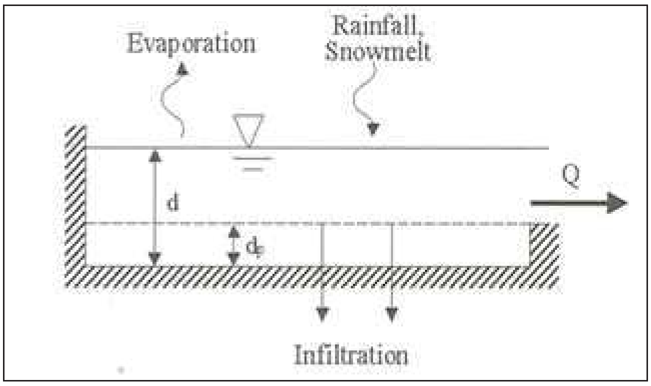


Figure 7.2 Non Linear Reservoir model of sub catchments (James, Rossman et al. 2008)

In SWMM run-off calculation the non-linear reservoir is established by coupling the continuity equation with Manning's equation.

Continuity equation:

$$\frac{dv}{dt} = A\frac{dd}{dt} = A * i^{*} - Q$$

Where:

V =volume of water on the subarea, m^3 and is A*d

d = water depth

t = time step, sec

A =surface area of the sub catchment, m^2

i^* =rainfall excess

Q = runoff, m^3/s

For the runoff we have Manning's equation

$$Q = A * \frac{1}{n} R^{2/3} S^{1/2} \text{ ....1}$$

But for a wide channel

$$R = \frac{A}{P} = \frac{W * Y}{W + 2Y} \approx \frac{W * Y}{W} \approx Y$$

where Y is depth

So by substituting this in equation 1

$$Q = W * Y * \frac{1}{n} Y^{2/3} S^{1/2} = W * \frac{1}{n} Y^{5/3} S^{1/2}$$

But $Y = d\text{-}dp$

$$Q = W * \frac{1}{n} (d - dp)^{2/3} S^{1/2}$$

So when the continuity equation is combined with manning's

$$\frac{dv}{dt} = A \frac{dd}{dt} = A * i - W * \frac{1}{n} (d - dp)^{2/3} S^{1/2}$$

$$\frac{dd}{dt} = i - W * \frac{1}{n * A} (d - dp)^{2/3} S^{1/2}$$

But width, slope, manning's coefficient and area are constant so

$$k = \frac{W * S^{1/2}}{n * A} \text{ And}$$

$$\frac{dd}{dt} = i - k * (d - dp)^{2/3}$$

${dd}/{dt}$ is solved at each time step using simple finite difference scheme. All the parameters in the LHS and RHS of the equation are taken as average over time step and the new equation will be:

$$\frac{d_2 - d_1}{\Delta t} = \frac{i_2 + i_1}{2} - k*((\frac{d_1 + d_2}{2}) - dp)^{2/3}$$

Where Δt= time step, sec and the subscripts 1 and 2 denote the beginning and the end of the time step. This equation is then solved for d_2 using a Newton –Raphson iteration. (James et al., 2008)

7.2.1.2 Flow routing in channels and pipes

The same concept of non-linear reservoir explained in sub catchments routing is used to calculate the flow in pipes. Continuity equation and manning's equation are coupled to produce the non-linear reservoir (James et al., 2008).

7.2.2 Model Set up

To set up the model first step will be to gather all necessary information about each element of the model. Next these different elements and parameters required in SWMM model are discussed in detail.

Sub-catchments

Delineating the sub-catchments is an important task which should be completed prior to other tasks and after sub-catchments are delineated rain gauges where precipitation data is fed into the model will be allocated for each sub-catchment. If ground stations are source of rainfall then using Tyson polygon or other methods precipitation for each sub-catchment will be calculated but as source of precipitation data is radar in this case a rain gage will be assigned for each grid and rain source for each sub-catchment will be the gauge in each grid where the sub-catchments are located.

Basically sub-catchments for SWMM model are imported from a SOBEK model developed by DHV for the same project but in SOBEK sub-catchments area information is calculated for each reach segment pipe and if the same is done for the SWMM there will be more than 1000 sub-catchments. So area in each pipe is added as per direction of flow and 103 sub-catchments are extracted from the information in the SOBEK model. Then 5m DEM data was analyzed using ArcGIS to determine extent of sub-catchments to define grid location of each sub-catchment as shown in figure 7.3.

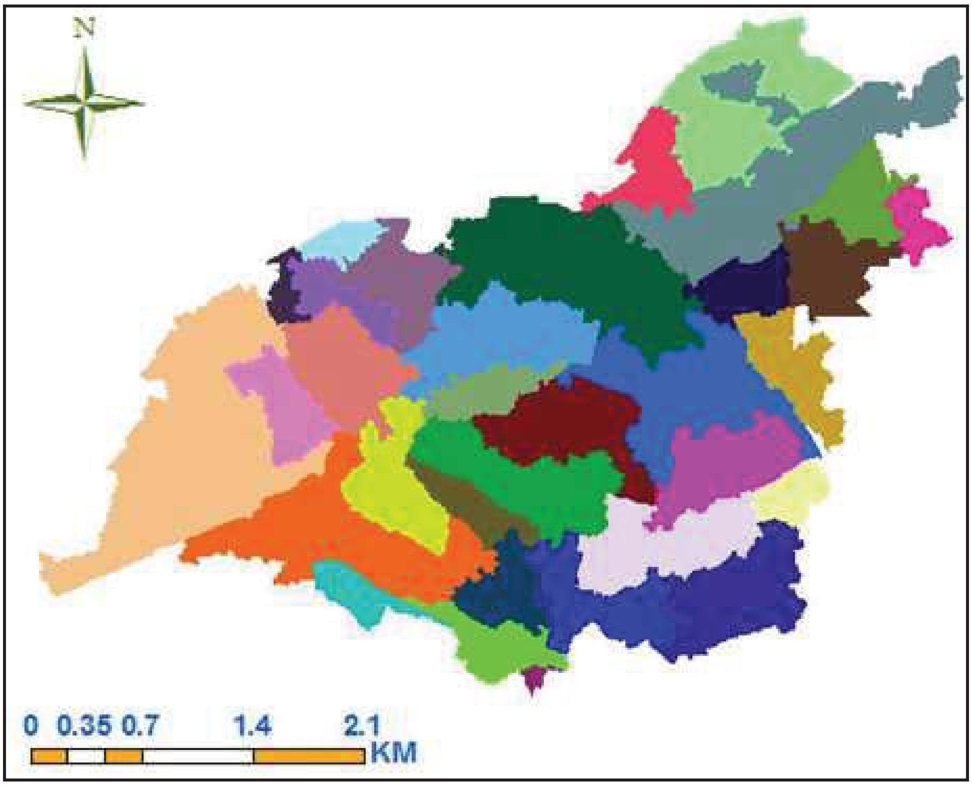


Figure 7.3 Sub catchments based on analysis on the 5m grid DEM data

In the SWMM model we need to provide the following information in the properties tab for each sub-catchment.

- Name and location of sub-catchments centroid
- Rain-gage for rain data input into sub-catchments.
- Outlet node
- Sub-catchments Area
- Width(each sub-catchments are assumed as square and width is calculated based on that)
- %slope of the sub-catchments
- %impervious of impervious layer
- N-impervious and N- pervious (Manning's coefficient)
- Depression storages(which are neglected in this study)

Node elements

There are 1002 junctions in the model and each Junction or node element properties include:

- Name and location of junctions
- Inflow (DWF and base flow if any are assigned at each junctions with all the daily, weekly and monthly peaking factors)
- Invert elevation above datum.

- Maximum depth (which can be expressed as elevation above datum or offset from invert elevation of manhole)
- Initial depth of water at the start of simulation (hot start file is used to take the previous time step value as an initial condition)
- Area for Ponding (water during flood event will be ponded on top of each node on this area until enough space to return to the system is available; if this area is zero then continuity error will be high as there will be much water lost out of the system).

Outfalls

There are 17 outfall nodes in the SWMM model out of which three are nodes through which flow exit from the system and remaining 14 are nodes for combine sewer overflows. Outfall element properties include name, location and invert elevation.

Conduits

There are 1042 conduits in the model out of which 182 have Egg shape, 855 Circular and 5 have closed rectangular shape. The internal storages are also modeled as conduits of closed rectangular Shape.

Conduit element Property

- Name and location expressed by Starting and Ending nodes
- Based on the Shape of the actual conduits from kiker data base four conduit shapes are used (Circular, Egg ,open rectangular and closed rectangular)
- Maximum depth of the conduit cross section which is the height in rectangular cross section and the diameter in circular cross sections
- Conduit length
- Manning's roughness coefficient
- Inlet and outlet offsets which can be depth or elevation of bottom of conduit from the invert elevation of the inlet or outlet node. In this research depth is used, which is the height different between 1 and 2 in figure 7.4.
- Information about flap gate which prevent back flow.

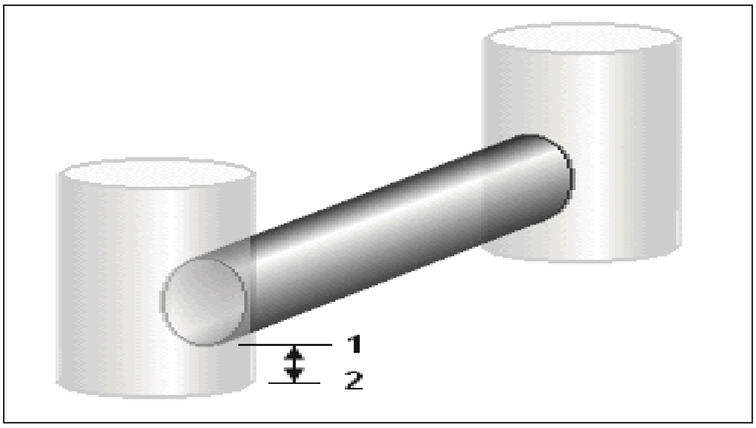


Figure 7.4 Offsets of conduits and flow regulators from the connecting node. (James, Rossman et al. 2008)

Weir element

There are 38 internal and external weir elements in the model and properties of these weir elements required in the model are

- Name and location indicated by Starting and Ending nodes
- Type of weir and in this case all weirs are Transverse
- Vertical height of weir opening
- Horizontal length of weir opening
- Inlet offset which can be depth or elevation of bottom of weir opening from the invert elevation of the inlet node (Figure 7) and here depth is used
- Discharge coefficient
- Information about flap gates, which is to prevent the backflow of water in the weir, here all weirs are with out Flap gate.

Orifice element

There are 12 orifices which control backflow at storage and weir locations with the following Properties:

- name and location expressed by Starting and ending nodes
- type of orifice (side or bottom) , here all orifices are modeled as bottom because of their actual location
- shape (circular or rectangular)
- height and width which are the dimensions of the orifice when it is pumping fully
- Inlet offset which can be depth or elevation of bottom of weir opening from the invert elevation of the inlet node. and in this research depth is used
- Discharge coefficient
- Flap gate if the weir have flap gate that prevent backflow

Pumps

There are 10 pumps in the model with the following properties:-

- Name and location of pump indicated by inlet and outlet node
- Pump curve
- Initial status
- Start up depth and shutoff depth

Rain-gage

Rain gauges are sources for the rain input in SWMM model and are assigned for each radar grid and to determine the grids ASCII format of rain data for one event is analyzed in ArcGIS using ASCII to Raster conversion tool. Map of Netherlands and pipe networks of Amersfoort drainage system are imported as shape file as shown in figure 7.5 then the coordinates of the pixels above Amersfoort city are determined.

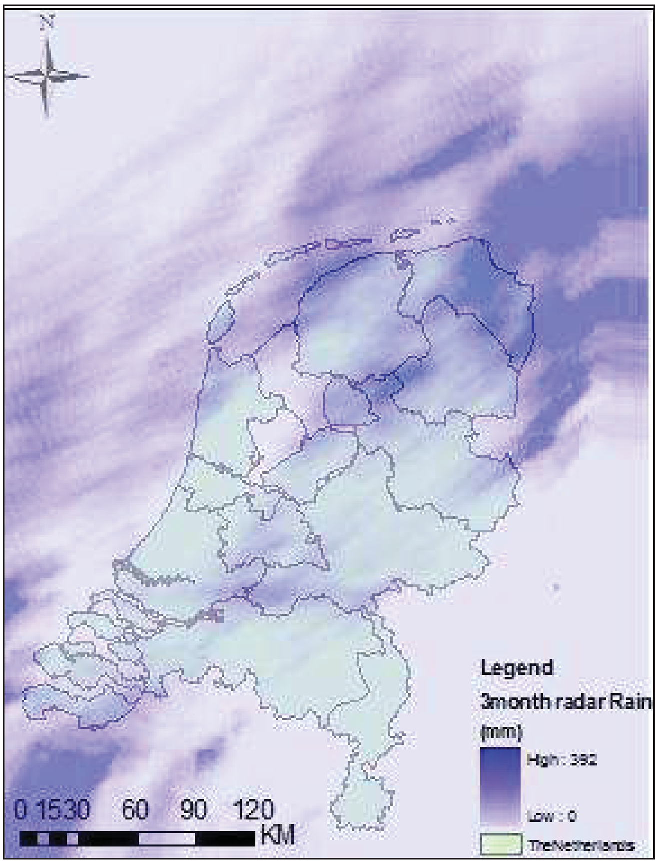


Figure 7.5 Raster map of a rain event together with map of The Netherlands

Then 6 km square grid is extracted from the raster at the location of Amersfoort city using clip tool in ArcGIS. Then the symbology of the clipped raster is adjusted for unique values to show the values of each grid cell with different color as shown in figure 7.6

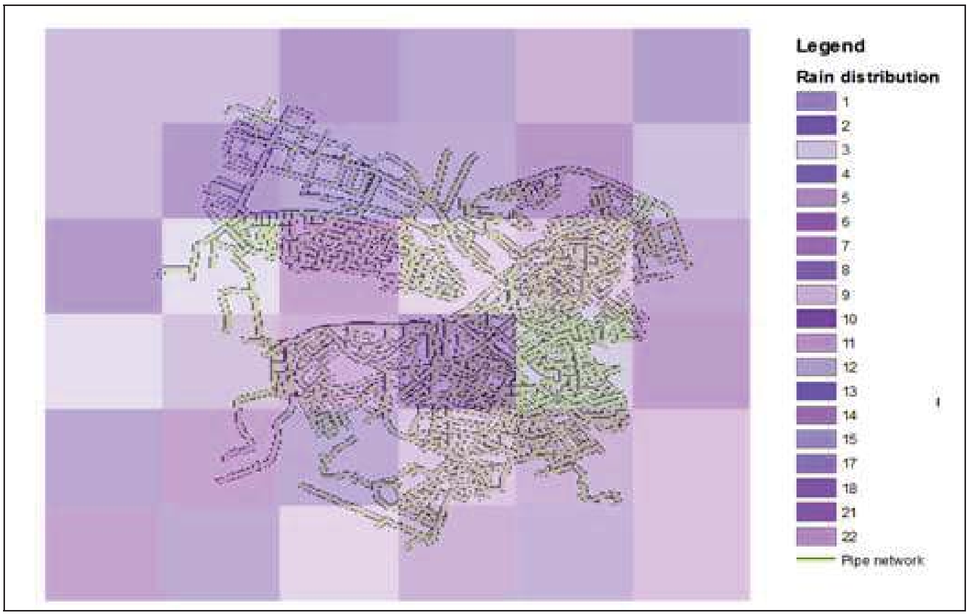


Figure 7.6 6x6 grids at the location of Amersfoort

Then the coordinates of the corner points are extracted. To upload an image in SWMM model two files are required the image file and a world coordinate file which have information about the coordinates and size of the image. World coordinate file is prepared using the information

from GIS(coordinates of the edges of the image) and Photoshop for the relationship between pixel size and distance. World coordinate file contains six lines with the following information

Line1:- real world width of the pixel in the horizontal direction (15.79).

Line2:-X rotational parameter (0).

Line3:- Y rotational parameter (0).

Line4:-negative of the real world height of the pixel in the vertical direction (-15.79).

Line5:-real world x coordinate of the upper left corner of the image (150790).

Line 6:-real world y coordinate of the upper left corner of the image (465836).

Then the image is uploaded as a background map in SWMM and the result is shown in figure 7.7

Each grid cell represents a 1kmx1km radar cell so rain gages are assigned for each cell (for simplification if a sub-catchments lies between two grids sub-catchments take the rain gage where more of the parts lie).

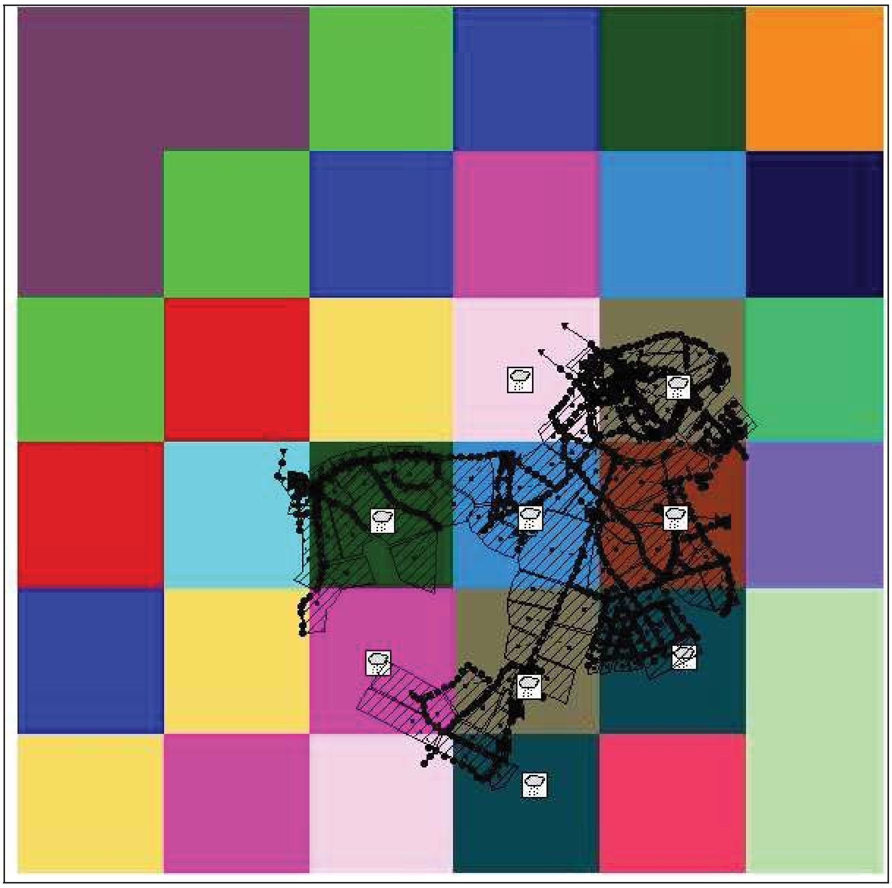


Figure 7.7 Urban drainage network together with radar grids

Then HydroNET tool is used to prepare time series of 5minute rain for these gages.

Properties of rain gages required by SWMM model:

- Name and location of rain gage in the study area

- Cumulative rain format is used, that is, each rainfall value represents the cumulative rainfall that has occurred since the start of the last series of the non zero value.
- Rain interval of 5 minutes is used as 5 minutes radar data is going to be used
- Data source is from file
- Detail of the data file name, station names in the file and rain units

After building the model with all the elements mentioned above the next step is to provide the simulation information in the option tab shown in figure 7.8. There are 5 different tabs where all required information which determines how the simulation model is going to run will be provided through this tab.

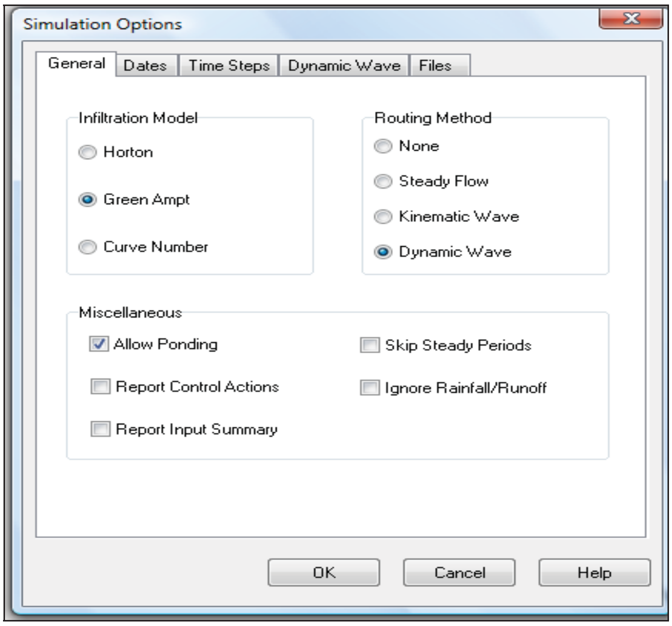


Figure 7.8 SWMM simulation option tab

In general tab the infiltration model is set to use Green Ampt for the infiltration model. Dynamic wave routing method and in Miscellaneous section Allow ponding is checked. The reason for selecting allow ponding tab is to keep the water which goes out of the nodes during simulation until there is enough volume to accommodate it back into the system. If ponding is not allowed the water will not return back into the system and will give high continuity error. Dates and Time steps tabs contain information about the starting date, ending date, and time steps for simulation and reporting. In Dynamic Wave tab information about inertial terms, super critical flow and main equation are supplied. Then in files tab filename for saving and using hot start file to be used during simulation are assigned.

7.2.3 Input Data Preparation

7.2.3.1 Dry weather flow

In order to simulate flow in the combined drainage system the Dry weather flow (DWF) and wet weather flow (WWF) values have to be known. Municipalities have their own standard methods of estimating these flows. Q for DWF is calculated based on

Q=ADWF x Peaking factor x Infiltration factor

Where:-

Peaking factor= (PDWF)/ (ADWF) = 2.5

Infiltration factor= PWWF/PDWF=2.0 and

ADWF= (sewage generation per capita) x (equivalent population)

ADWF- average dry weather flow

PWWF- peak wet weather flow

PDWF-peak dry weather flow

Infiltration Factor is the allowance for surface/groundwater leakage into the wastewater. Infiltration factor depends on the condition of the sewer network and a number of associated variables such as the sewer pipe material, age, quality of construction, whether the sewer has been rehabilitated and the quality of rehabilitation. This factor also depends on rainfall and ground water level (Brockies, 2009). In table 7.1 per capita sewage generation, 200 L / person / day, is based on historical water consumption and wastewater flow measurement data across the city. Subsequent reviews of this rate of wastewater production have reaffirmed 200 L / person / day is the average rate of wastewater production per capita across Amersfoort City (RIONED, 2008).

Table 7.1 DWF calculation for flow into each node

Node Id	Inhabitants	Sewage generated per capita(l/c/d)	Infiltration factor	Peak factor	Average dry weather flow (l/d)	Flow (m^3/s)
0-40058	2062	200	2	2.5	2062000	0.024
0-70388	2600	200	2	2.5	2600000	0.030
0-70457	2600	200	2	2.5	2600000	0.030
0-100157	2062	200	2	2.5	2062000	0.024
0-100251	2062	200	2	2.5	2062000	0.024
0-100549	2062	200	2	2.5	2062000	0.024
0-120125	2600	200	2	2.5	2600000	0.030
0-120185	1350	200	2	2.5	1350000	0.016
0-280089	3000	200	2	2.5	3000000	0.035
0-280103	2600	200	2	2.5	2600000	0.030
0-310028	2600	200	2	2.5	2600000	0.030
0-390049	1750	200	2	2.5	1750000	0.020
0-390164	1750	200	2	2.5	1750000	0.020
0-390181	2600	200	2	2.5	2600000	0.030
0-390246	1088	200	2	2.5	1088000	0.013
0-660090	2600	200	2	2.5	2600000	0.030
0-660271	2600	200	2	2.5	2600000	0.030
0-660318	3000	200	2	2.5	3000000	0.035
0-660342	2600	200	2	2.5	2600000	0.030
0-660396	3000	200	2	2.5	3000000	0.035

Although the ADWF is calculated based on an average per capita wastewater generation, the instantaneous wastewater flow varies with time of the day, day of the week and also seasonally. This variation is taken into account in the Design Flow by using a Peaking Factor

(PF). This value can be determined by analyzing the flow in the drainage system for a longer period considering only the DWF (excluding flows while there is rain). Figure 7.9 gives diurnal values of the peaking factor used in the model. The seasonal and weekly variations of flow are neglected because information is not available.

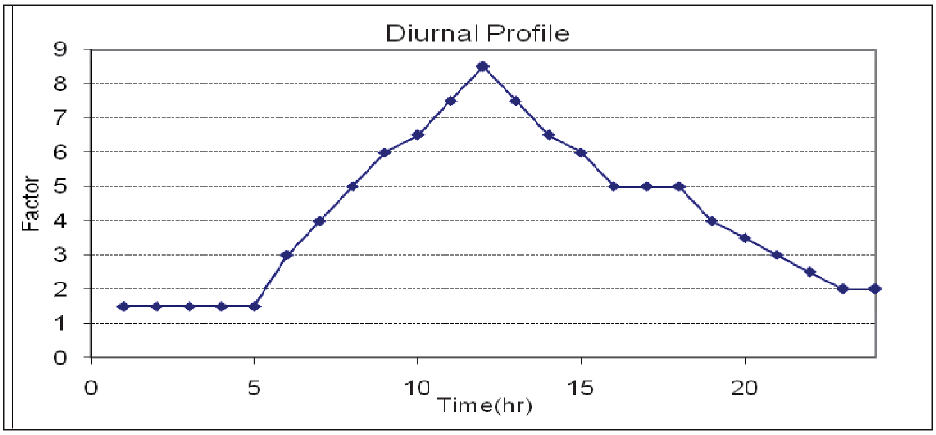


Figure 7.9 Diurnal variation of peaking factor

7.2.3.2 Wet Weather Flow (Rain data)

For design rain event with 2 years return period and two hours duration is used (event of 1/1/1995) with 10 % increase for climate change (Gemeente-Amersfoort, 2008). The 10 % increase of design storm for climate change consideration is important because as urban drainage systems are designed with a design life span of 10 years or more, possible future increase of loading in the system should be considered. Based on this design event the capacity of the existing system will be evaluated and possible remedies will be suggested if there is any flooding or CSO problem. For demonstrator part real time radar data will be used.

7.2.4 Model Calibration

7.2.4.1 Overland flow

SWMM does not compute overland flow, nor does it compute or require a time of concentration. It stores precipitation in a 'reservoir' and discharges it to an inlet according to Manning's equation where flow width is specified by the width parameter and height is the ponded water depth. So flow metering data should be used for the sub-catchments in the watershed to adjust the characteristic width parameter until a good fit exists between the observed and simulated hydrographs. Unfortunately for this project there is no discharge measurement for watersheds (sub catchments) and it was not possible to do calibration of overland flow.

7.2.4.2 Flow routing in pipes

The result of the SWMM model for an event of January 23, 2009 is compared with the available measurements. The measurements which are available are only in storage basins so the result comparison is limited to checking the measured and simulated water levels in the storage basins and this result shows reasonable accuracy as can be seen in the result depicted in figure 7.10a. The RMSE and the Nash-Sutcliffe efficiency value are 0.13 and -0.56

respectively. From the RMSE test it can be seen that the simulated and measured results have less difference but the Nash-Sutcliffe efficiency is negative which means observed mean is better predictor than the model which is the case because the measured water level in the period considered have almost a constant value. Further comparison with measured data and then calibration of the model was not possible because of limitation of measured data.

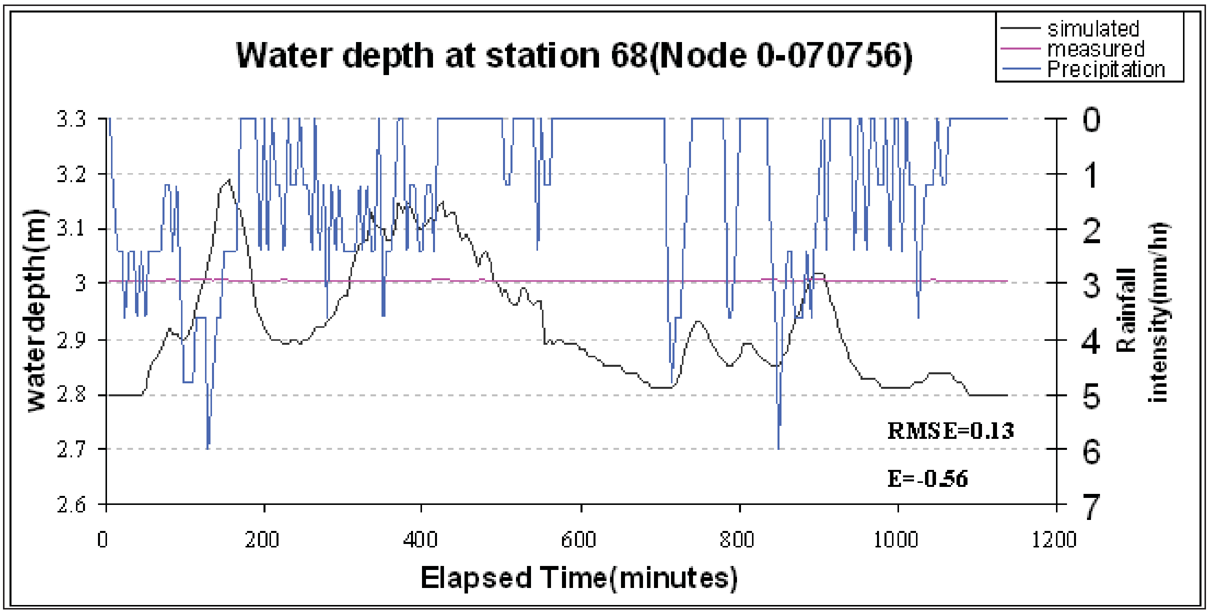


Figure 7.10a comparison of measured and simulated results of SWMM model at storage basin in station 68.

7.2.4.3 Comparison of SWMM and SOBEK models

To check for consistency of the SWMM model with the SOBEK model results, for the same rain event (design storm), the two models are compared for locations indicated on figure 7.10b.

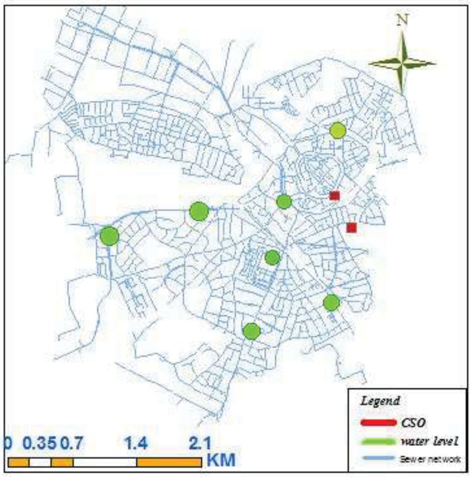


Figure 7.11b Map showing locations where results are compared between SWMM and SOBEK model

From the plot of result from SWMM and SOBEK model visually it can be seen that the results are almost the same but this could be scale dependant so statistical methods root mean squared error (RMSE) and Nash–Sutcliffe efficiencies (E) are used. Root mean squared error

(MSE) and the Nash-Sutcliffe efficiency (E), are the most widely used criteria for calibration and evaluation of hydrological models with observed data (V.Gupta et al., 2009).

$$E = 1 - \frac{\sum_{t=1}^{T}\left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q_o}\right)^2}$$

Where Q_o is measured discharge, and Q_m is simulated discharge. $Q_o t$ is measured discharge at time t. Nash–Sutcliffe efficiencies can range from −∞ to 1. An efficiency of 1 (E = 1) corresponds to a perfect match of simulated discharge to the observed data. An efficiency of 0 (E = 0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero (E < 0) occurs when the observed mean is a better predictor than the model or, in other words, when the residual variance (described by the nominator in the expression above), is larger than the data variance (described by the denominator). Essentially, the closer the model efficiency is to 1, the more accurate the model is.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(x_{1,i} - x_{2,i})^2}{n}}.$$

Where X_1 is observed discharge and X_2 is modeled discharge. $X_{1,i}$ is observed discharge at time t.

When the RMSE is close to zero the simulated and measured data sets have less difference. Using result from the SOBEK model as measured or observed data set the two values are compared and the result is presented below each graph.

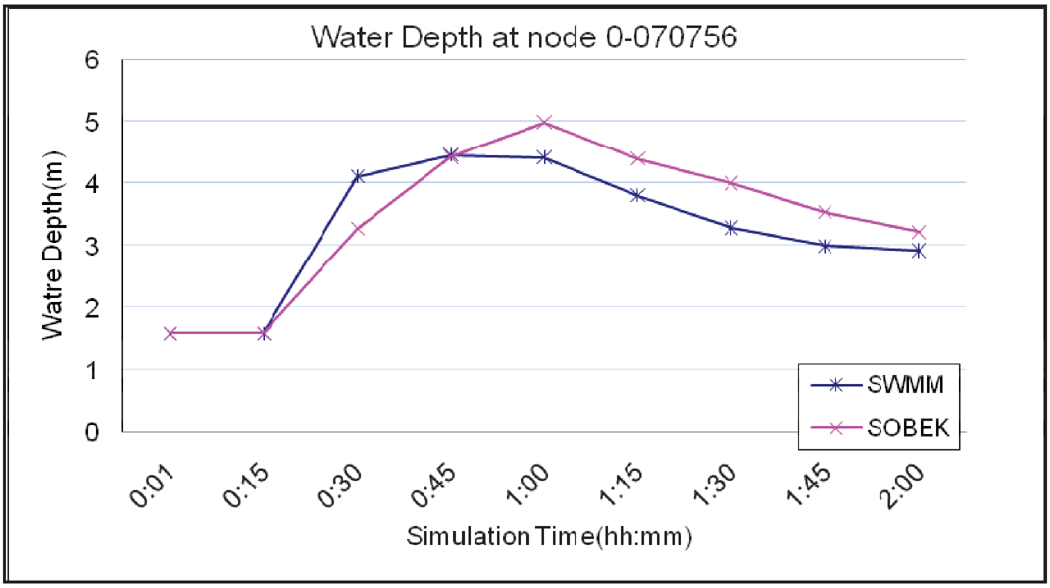


Figure 7.12 SWMM vs. SOBEK result of water depth at node 0-070756 (RMSE=0.505 and E=0.76)

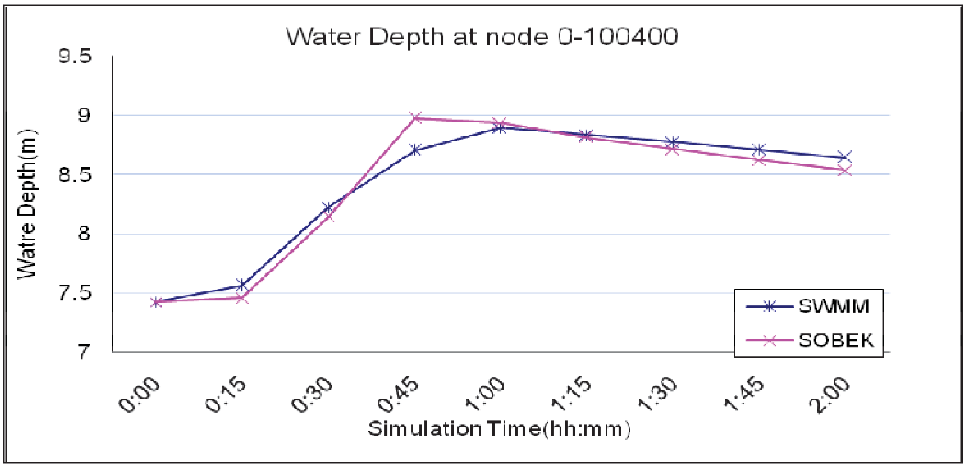


Figure 7.13 SWMM vs. SOBEK result of water depth at node 0-100400 (RMSE=0.114 and E=0.953)

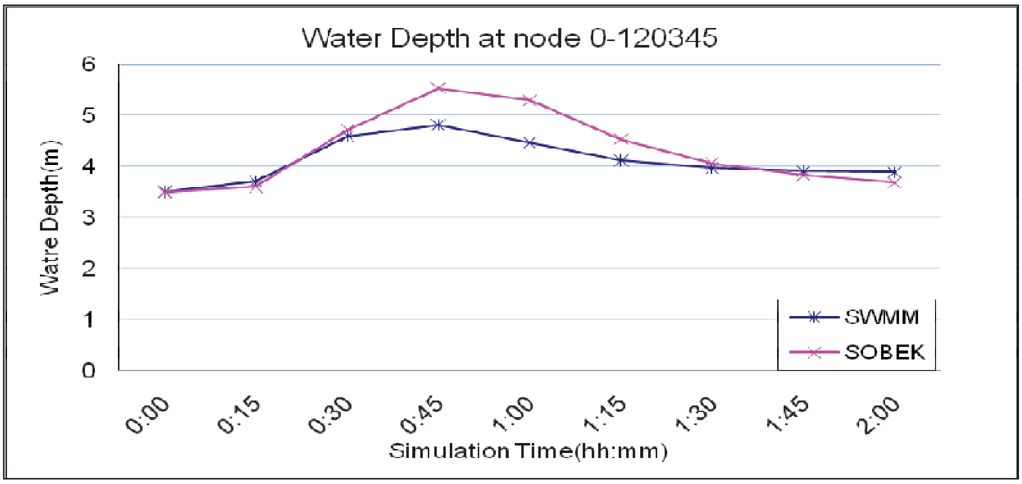


Figure 7.14 SWMM vs. SOBEK result of water depth at node 0-120345 (RMSE=0.406 and E=0.00)

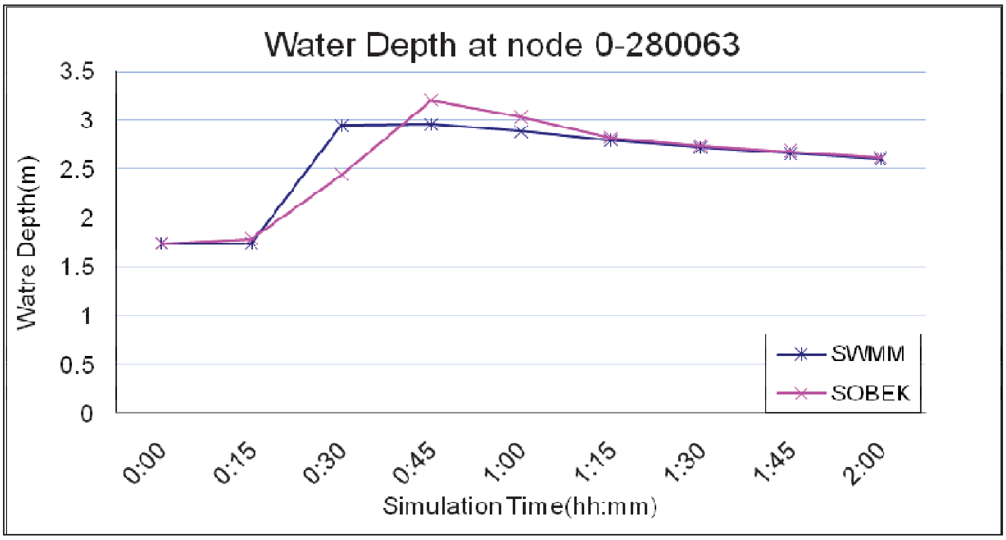


Figure 7.15 SWMM vs. SOBEK result of water depth at node 0-280063 (RMSE=0.196 and E=0.82)

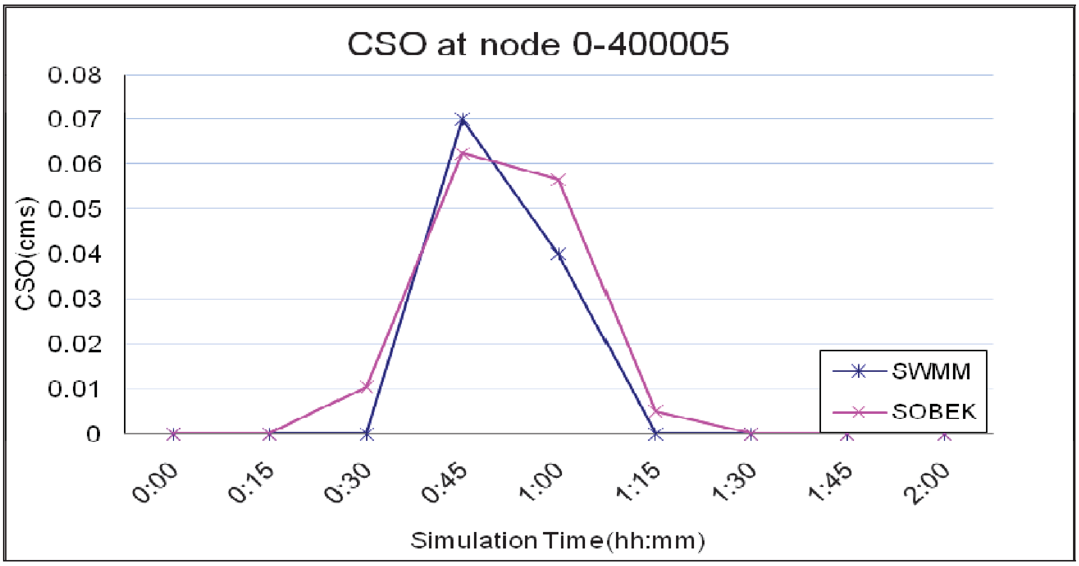


Figure 7.16 SWMM vs. SOBEK result of CSO at node 0-400005 (RMSE=0.007 and E=0.907)

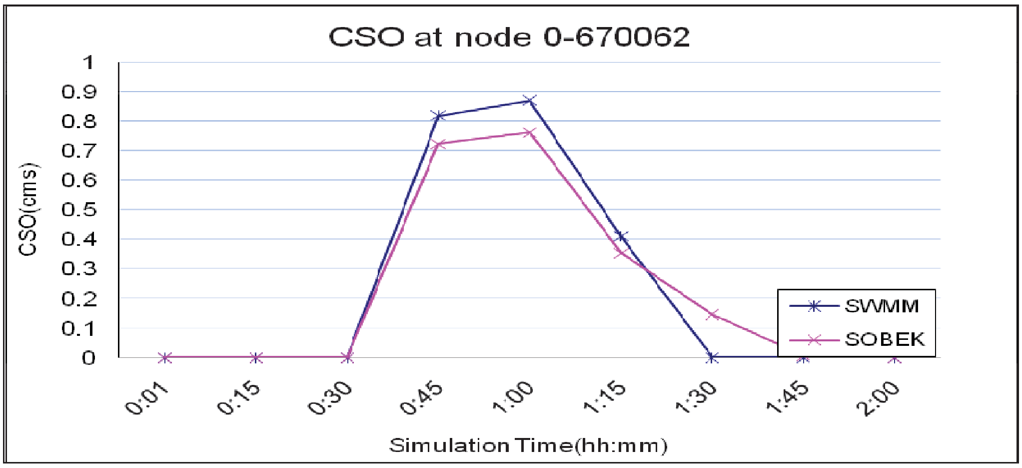


Figure 7.17 SWMM vs. SOBEK result of CSO at node 0-670062 (RMSE=0.07 and E=0.96)

As depicted in figures 7.11 through figure 7.16 the results are found to be reasonably comparable. For the CSO further analysis is made to see the difference between the total volumes of CSO. For node 0-400005 the result of CSO volume from the SWMM model is found to be 121 m^3 while that of SOBEK model result is 124 m^3 and for node 0_670062 for SWMM it is 1794 m^3 while that of SOBEK is 1738 m^3.

This comparison shows that the result of SWMM model simulation is comparable with that of the SOBEK model.

7.3 Offline Flood Management

Small flooding (water-on-street) occur after high rain event; Figure 7.17 depict flood on street after an event in August 2006. Based on result of the analysis of SWMM model loaded with the design event, which is an event with a 2 year return period and have been increased by 10% to account for climate change (RIONED, 2008), alternatives mentioned in next paragraph will be examined to solve flooding problem if there is any.

Figure 7.18 Water-on-streets after a rain event in August 2006

These three options will be considered to solve flooding problem.

1. Hold the excess water in upstream pipes using control gates. Detailed analysis on capacity of upstream pipes will be made to see if there is unused storage during flooding.
2. Divert the excess water to a node in another location using pump. If the first measure which is holding the excess water upstream can not be applied because there is not enough storage for the excess water then capacity of pipes in the vicinity of the flooded area will be checked to analyze the option of using pump to divert the excess water to a location where there is enough storage as shown.
3. Implement a new offline storage tank. If the above two options can not be used then in part of the city where flooding occur existing UDS network is utilized in full capacity for the design storm. In this case increasing pipe capacity or implementing storage facilities could be a solution. In this study implementation of additional offline storage will be evaluated for solving flooding problem. The storage location is indicated by circle in figure 7.18.

Figure 7.19 Map of the area with water-on-street after simulation using design storm

This analysis on options mentioned above showed that implementing additional storage is the solution to solve flooding problem for this case study. Two storage tanks and four weirs, which divert water into the storages from four manhole nodes, are implemented in the UDS network. This analysis will be discussed in detail in Result and Discussion part of the thesis.

7.4 Online SWMM modeling with real time radar data

As explained in the research objective the demonstrator is a tool which will collect recent rainfall data from radar, run SWMM model and present the simulation result together with measured data in a web page and this should be an automated process. A radar rain forecast with lead time of two hours is available with 1 km_x_1 km spatial resolution and 5 minutes time step but currently web services to access this data on real-time from KNMI are not available and the demonstrator will use synthetic data for the forecast part. For possible implementation of forecasted data from KNMI in the future the demonstrator will use two hours as a time frame to present simulation result for forecasted and current rainfall data. So every two hours the automated process updates input data, runs SWMM model and presents result on the web pages. Updating information at a time interval as low as 10 minutes, which is approximately time it takes to gather all the required data and run the SWMM model, is also possible.

In order to achieve this objective a code is developed using Visual Basic. The main reason Visual Basic is chosen for this task is because the HydroNET web services, which collect radar rain data, is developed in Visual Basic .NET frame work so to integrate everything into one the other parts of the demonstrator were also developed using Visual Basic. There are basically four parts in the code.

- Radar rain data collection
- Prepare input file for the SWMM model using updated rain data
- Run SWMM model and save out put in report file
- Read result from report file and prepare graphs

These basic parts are summarized in the flow chart shown in figure.7.19

The first function is the main component where the 5minutes rain radar data is accessed from web services of HydroNET. The code checks for a recent data in the server of HydroNET where normally data with 10minutes lag is available. This time series of data is prepared and saved in the hard disk of the computer which acts as a server for the demonstrator. The time series of 5 minutes interval is with recent date as starting point and going backward to a number of steps based on for how long we want to access the data and run the simulation model.

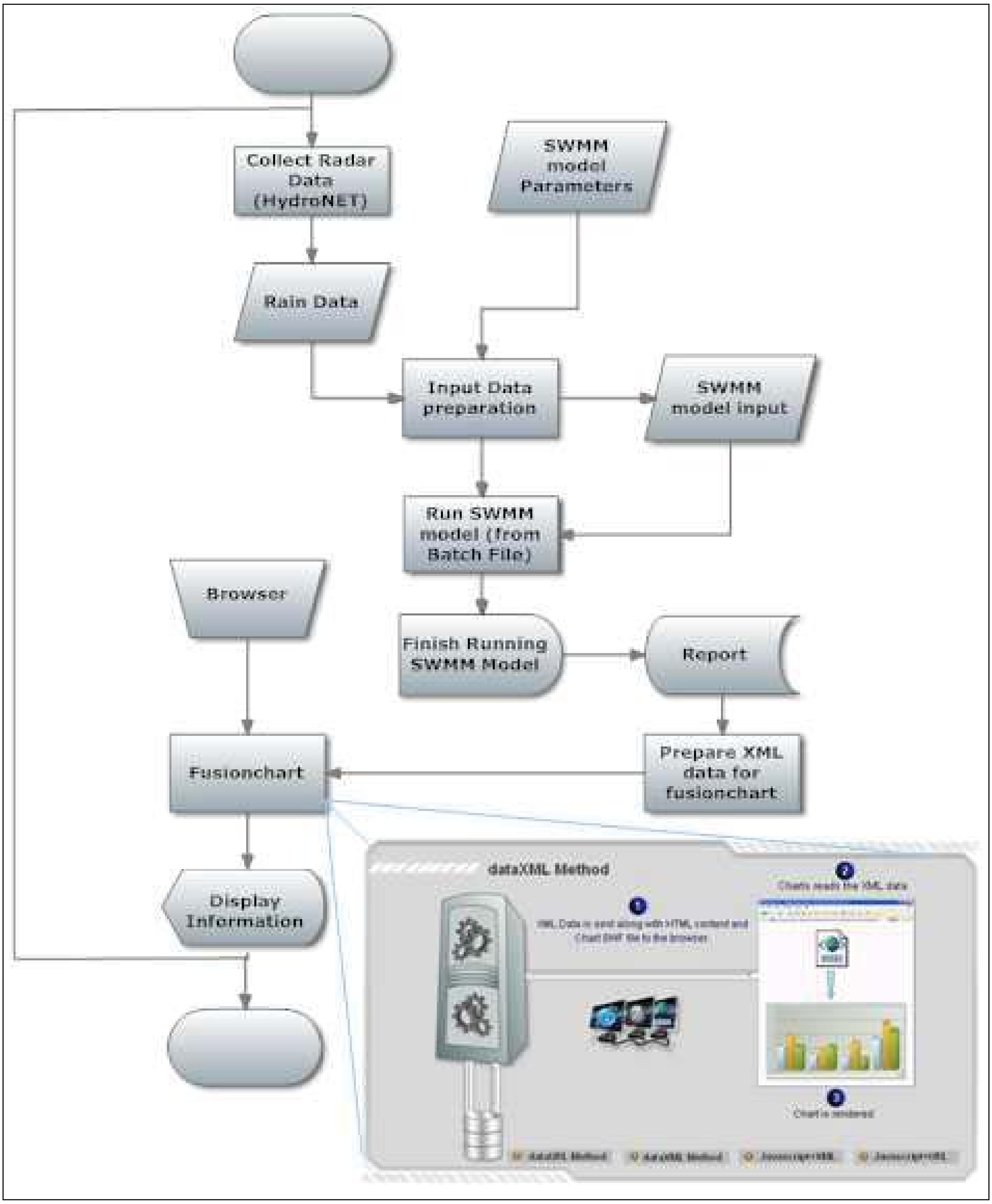


Figure 7.20 Flow chart for the demonstrator code

To collect data for two hours and run the model for this data in the past two hours we will make the code in this part to run 24 steps, in each step we collect 5 minute data.

The code collects data for 36 grids with the arrangement shown in figure 7.20 and save it in one file as a time series of each stations starting from station ST1 to ST36.

ST1	ST2	ST3	ST4	ST5	ST6
ST7	ST8	ST9	ST10	ST11	ST12
ST13	ST14	ST15	ST16	ST17	ST18
ST19	ST20	ST21	ST22	ST23	ST24
ST25	ST26	ST27	ST28	ST29	ST30
ST31	ST32	ST33	ST34	ST35	ST36

Figure 7.21 Locations of radar grids

In figure 7.20 grids shaded with green color are of interest to the model and grid (station) and its corresponding rain gage name in the SWMM model are shown in table 7.2.

Table 7.2 Rain gage name Vs grid station in the SWMM model

RAINGUAGE	1	2	3	4	5	6	7	8	9
STATION	ST21	ST27	ST16	ST22	ST28	ST34	ST17	ST23	ST29

The second function is dedicated to preparing the input file for the SWMM model. Using user interface of SWMM all the information required to model the urban system was inserted. This information includes the location of hot start files and rain gage files. Then the input data is saved into a file and is used as a general input file for all the parameters of the SWMM model. The task of the second function is to use this input file and rainfall file saved in the first function to create a new input file with recent information about the start and end date of model simulation and start and end data of reporting. Then this new input with updated information is saved into a file.

Function three basically has a task of calling the command line to run SWMM and save the result in a report file. The input for this function is a batch file which contains command line SWMM, input file and report file.

"C:\Program Files\EPA SWMM 5.0\SWMM5.exe" input1.txt reporte.txt

In the report file the out put result for selected nodes is reported and these values are going to be used later in the final part of the demonstrator. Function three makes sure that the task of running SWMM from command line is finished before it exits so that error will not occur in the next stages of the code while trying to read a report file which is not yet ready.

Function four reads result from the report file and prepare all the tables with information on simulated water depth, invert elevation and ground surface elevation of the manholes at all the stations. This function will open and read through the report file write the result of the selected nodes to tables and save this tables with *.php extension.

All the functions are then put together in one main function, compiled and the *.exe file from the debug file of the compiled function is put in windows task manager to run it automatically every half an hour. So all the data is updated and simulated model results are saved into file every half an hour.

7.5 Web page

The final part of the demonstrator is to present the result in a web page. Main page is designed using HTML and Google map is imbedded in it so that the page will be more interactive. All the stations in the project area are marked in the Google map with a link to a page where the simulated water depth at the manholes is indicated. ArcGIS is used to find the longitude and latitude of the stations as it is required to embed it in Google map for showing locations of stations and these stations are listed in table 7.3.

Table 7.3 Station names and locations

No.	Station	Name	Node name in Kiker	Latitude	Longitude
1	068	BBL Kersenbaan	070756	52.15	5.384
2	030	Sint Andriesstraat	0310022	52.156	5.396
3	031	Waltoren	0680001	52.158	5.397
4	038	Kleine Spui	0660502	52.16	5.386
5	056	BBL Langegracht	0660606	52.158	5.388
6	072	BBL Leusderweg	070668	52.138	5.377
7	075	BBB Smallepad	0660592	52.159	5.385
8	076	Lg Smallepad brandriool	0670002	52.159	5.384

These stations together with outfall and storage locations will be indicated using icons in the Google map of the main page at their geographical location and each icon will have a link to a page showing charts of rainfall together with water level, out fall discharge or percentage of utilized capacity of storage tanks depending on what the icon represents at the selected location. These charts to display simulated result are designed using fusion chart, which works with flash player. The charts are plotted dynamically using prepared input xml files and a format for each chart type which is saved in the same folder together with the xml files. All the xml files are prepared by function four in the Visual Basic code (Appendix 1).

XAMPP software package, which has Apache server, PHP engine and MySQL all together, is used on the server computer to make the WebPages globally accessible using the IP address of the server computer (Seidler, 2009). Figure 7.21 summarizes all tasks involved when a user initiates a request using a web browser.

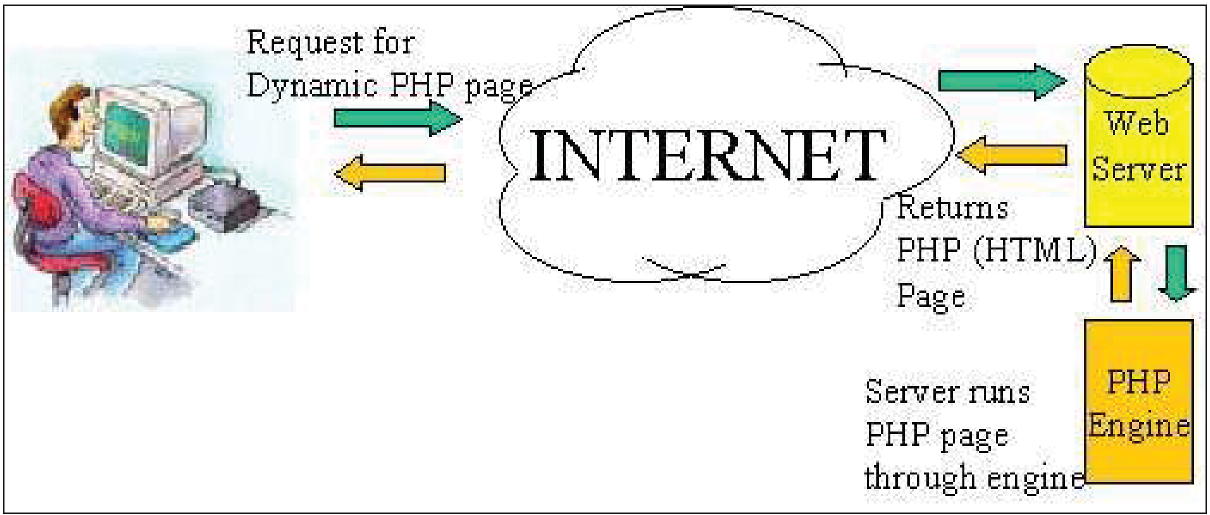


Figure 7.22 Data flow in the web pages client and server side

7.6 Proposal for Real time Flood management

After implementing two storages in the system, during peak flood event all the water can be diverted into these storages but if a weir with a controlled crest level is provided crest levels can be fixed based on how much water is needed to be diverted into the storages hence the amount of water which enters into the storages is controlled and energy cost for pumping the water back into the system will be minimized. Minimizing energy cost ,which means lower operational cost, is not top priority in urban drainage system but improved usage of drainage systems with lower cost is economical optimization (Huber et al., 1991).

To achieve this economical optimization crest level of the weirs, which divert water from nodes to the offline storage facilities, are fixed in such a way that will minimize cost of pumping latter: the crest level of the weir will be lowered only to an optimal level which will solve flooding. A rain forecast with lead time of two hours is going to be used in the SWMM model and the optimizer will work by running SWMM model with different weir crest level until optimal crest level is found. To get the optimal crest level of the weirs optimization algorithms like Genetic Algorithm (GA) could be used. GA is a technique used in computing to find an exact or approximate solution in optimization and search problems by mimicking genetic processes of biological organisms (Davis et al., 1991). Using rain forecast data of two hours in advance the system will react proactively by fixing crest levels based on results of SWMM simulation model in such a way that there will be no flood on streets and only portion of storm water which could cause flood on streets is diverted into the storages.

The running time of the optimizer should be lower than lead time for rain forecast, which is two hours in this case, as otherwise the forecasted rain event will pass before the UDS reacts. Depending on the time it takes to run the model, number of generations and population size in each generation running GA optimizer may take some time. For example a run with 20 generations and 20 population in each generation takes approximately 20 hours (each SWMM run taking 3 minutes) using current speed of average personal computer. So an iteration loop will be used to solve this problem of optimizing crest level. In a code with Visual Basic the SWMM model with rain forecast as an input will run in a loop by changing the weir crest level and calculating total flooding for each iteration. The crest level will be

plotted with calculated flood volume for each iteration step and the optimal crest level then can be fixed.

8. RESULT AND DISCUSSION

8.1 Variability of Rainfall in the research area

Urban drainage systems have high sensitivity to spatial and temporal distribution of rainfall with their rapidly reacting small scale sub catchments (Schilling, 1991). The high spatial and temporal resolution radar rainfall data available from KNMI was analyzed for variability by selecting four radar grids of 1 km x 1 km size in the research area and in figure 7.4 the time series of these rainfall data for these four grids are plotted.

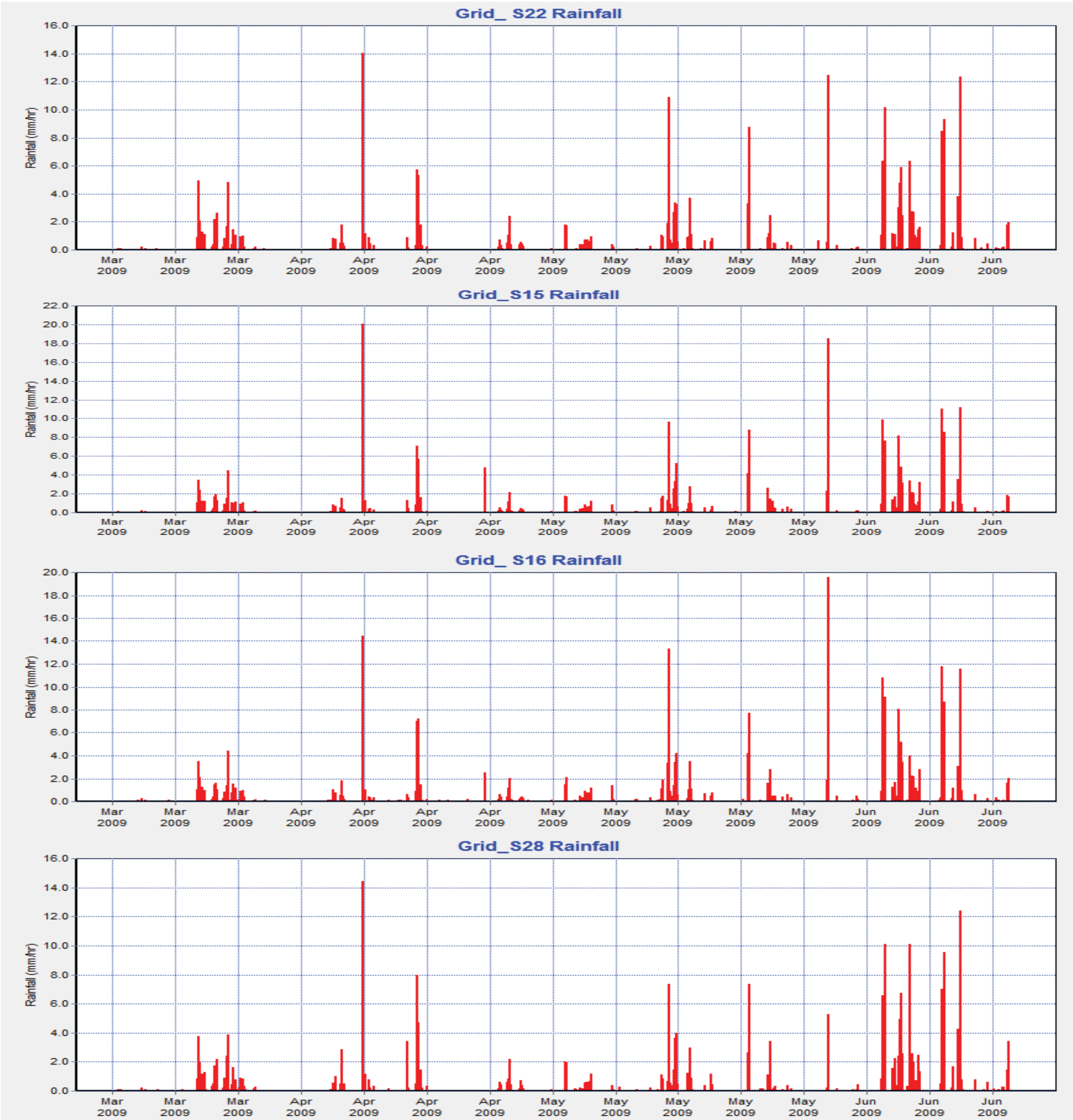


Figure 8.1 Time series of rainfall for station ST1 to ST4

The general pattern of the time series for the four stations is similar and to find out if there is variability among stations each time step rainfall data is analyzed by plotting the rain

intensity on each grid. Intensity values of an event of 11th of June 2009 20:50GMT is plotted in figure 8.2 with different colors to depict different rain intensities ranging from lower than 0.5 mm/hr to higher than 2 mm/hr.

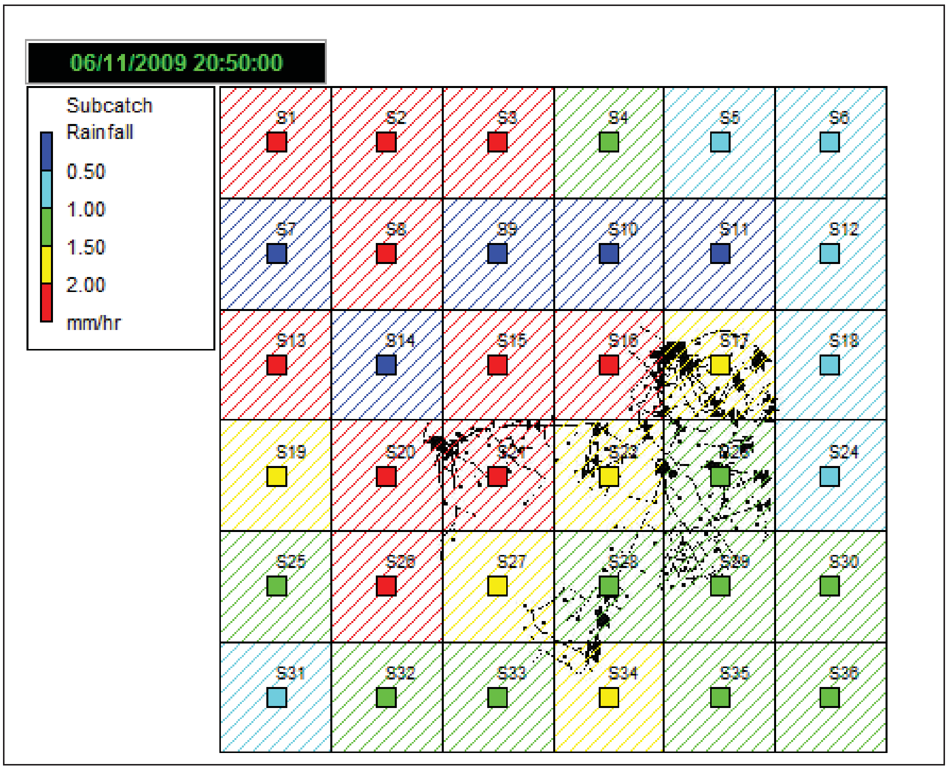


Figure 8.2 Rain intensity variation in 1kmx1km grids of a 5 minutes data depicted with different colors

Time series of grids with different colors are plotted in figure 8.3 and it can be seen from the time series that there is indeed variation for big rain events. The three pointes selected in these graphs show events with big difference of rainfall compared with neighboring grid. For instance let us have a look at the value of rainfall for the four events at 18:00 hour GMT on 10th of June. The values are 4mm/hr, 6.4 mm/hr, 10mm/hr and 4.75mm/hr and for one grid the value is more than twice of the other two grid values. The simplest method of analyzing the interrelationship between two variables is the correlation analysis and it is defined as the association of two variables. High correlation shows high degree of association hence low variability. The correlation coefficient between tow variables R is defined as:

$$R = \frac{\sum_{j=1}^{n}(x_j - \bar{x})(y_j - \bar{y})}{\sqrt{\sum_{j=1}^{n}(x_j - \bar{x})^2}\sqrt{\sum_{j=1}^{n}(y_j - \bar{y})^2}}$$

Where: n is the number of observations,

x_j and y_j are the j^{th} observations of variables x and y and

$\bar{x}$ and $\bar{y}$ are mean values of x and y

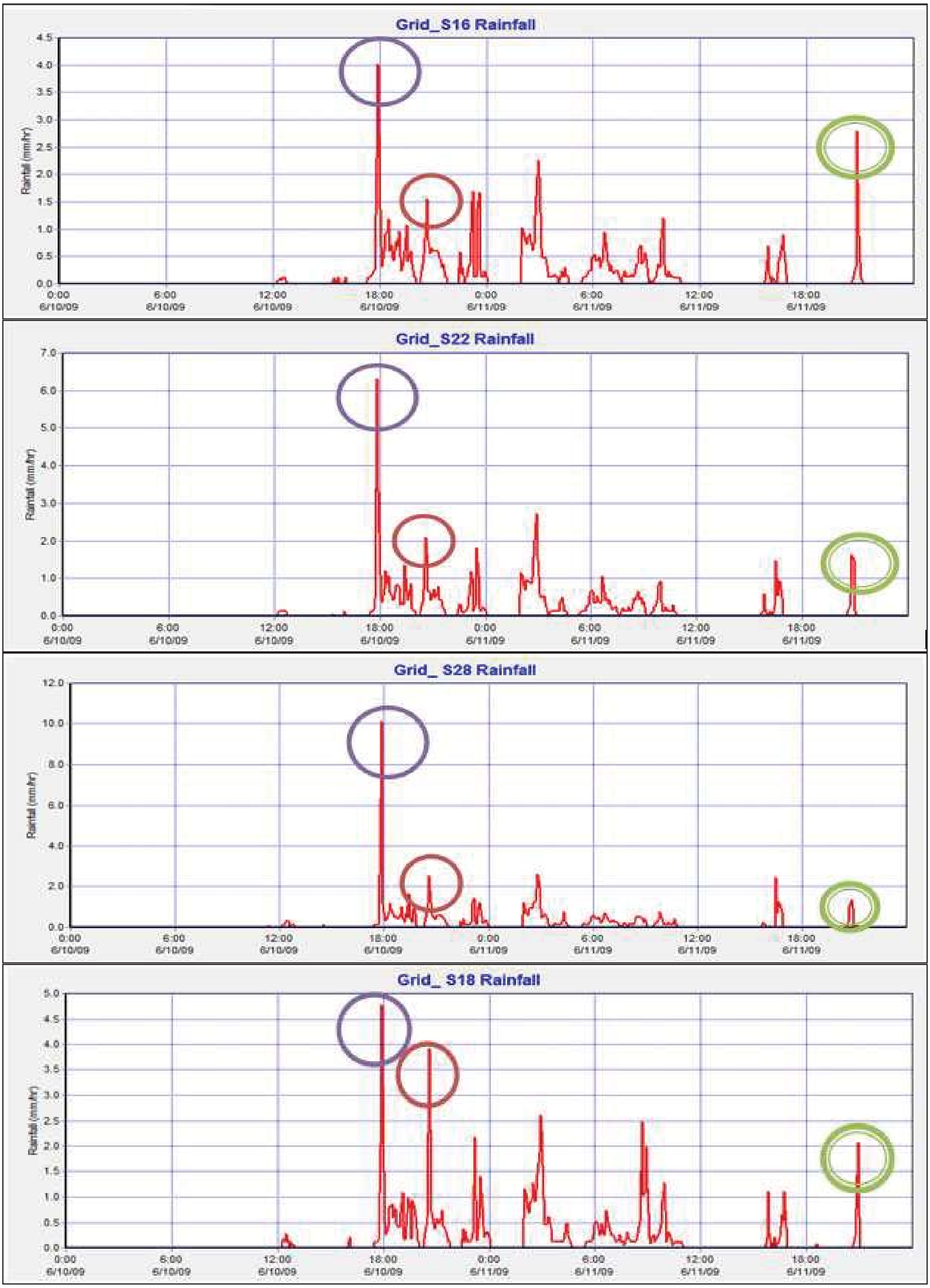


Figure 8.3 Time series showing the variability of big events

The data used for this analysis is for a period of four months starting from March 2009 to June 2009. The actual variability could be even more than what is observed in the data for

this period as events of high rainfall recorded during this period are limited so if the data is analyzed for a longer period the result observed will be improved.

In figure 8.4 to figure 8.9 rainfall data coefficient of correlation values for grids at different distance and different time resolution are plotted together with graph of R equals to unity (which basically means there is no variation and one variable can be predicted from the other with out error) for comparison. The same data plotted as time series in figure 8.1 are used for this analysis.

The coefficient of determination defined by R^2 is shown in the same figure and the closer this value is to unity the more the association between the two variables and hence better estimates can be made from each other. The coefficient of determination (R^2), which is the square of the correlation coefficient, is indicated in the trend lines as it gives the proportion of the variance (fluctuation) of one variable that is predictable from the other variable. For example in figure 8.4 for the 5 minutes data R^2 is 0.795 so 79.5% of the prediction of one variable from the other could be explained from the relationships between the two data sets while the remaining 20.5% remains unexplained.

The 5 minutes data is used to prepare the other 15 minutes, 1 hour and 1 day data sets using subtotal function of excel by aggregating the 5 minutes data accordingly.

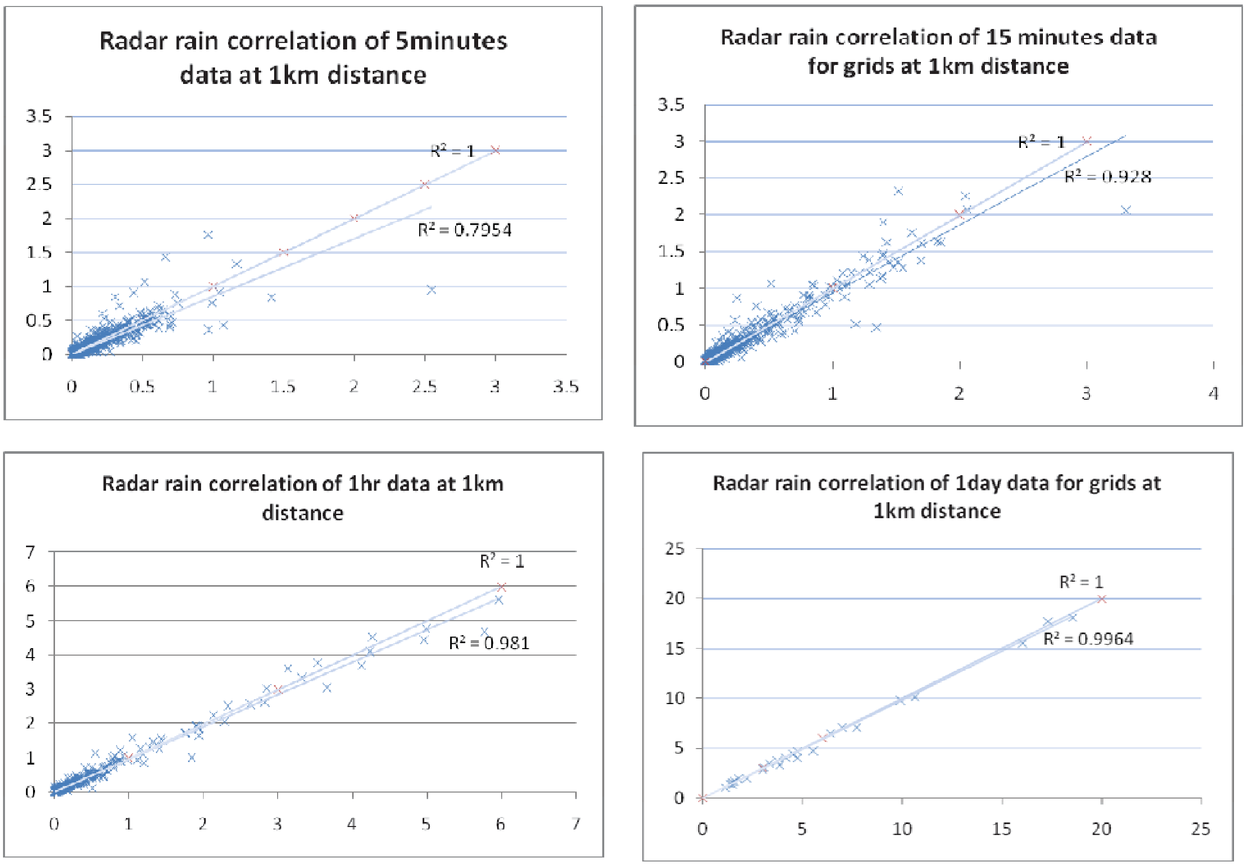


Figure 8.4 Radar Rain Correlation of 5minutes data for grid cells located at 1km distance

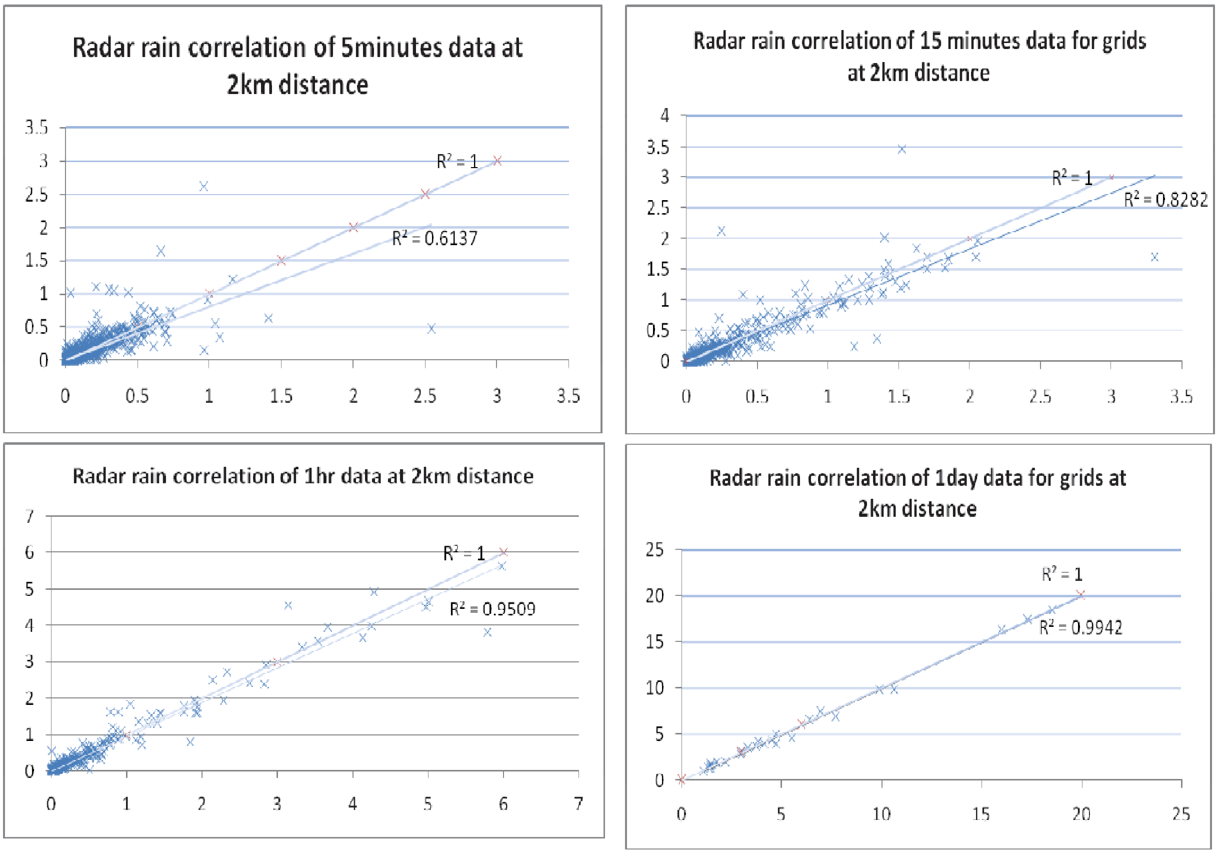


Figure 8.5 Radar Rain Correlation of 5minutes data for grid cells located at 2km distance

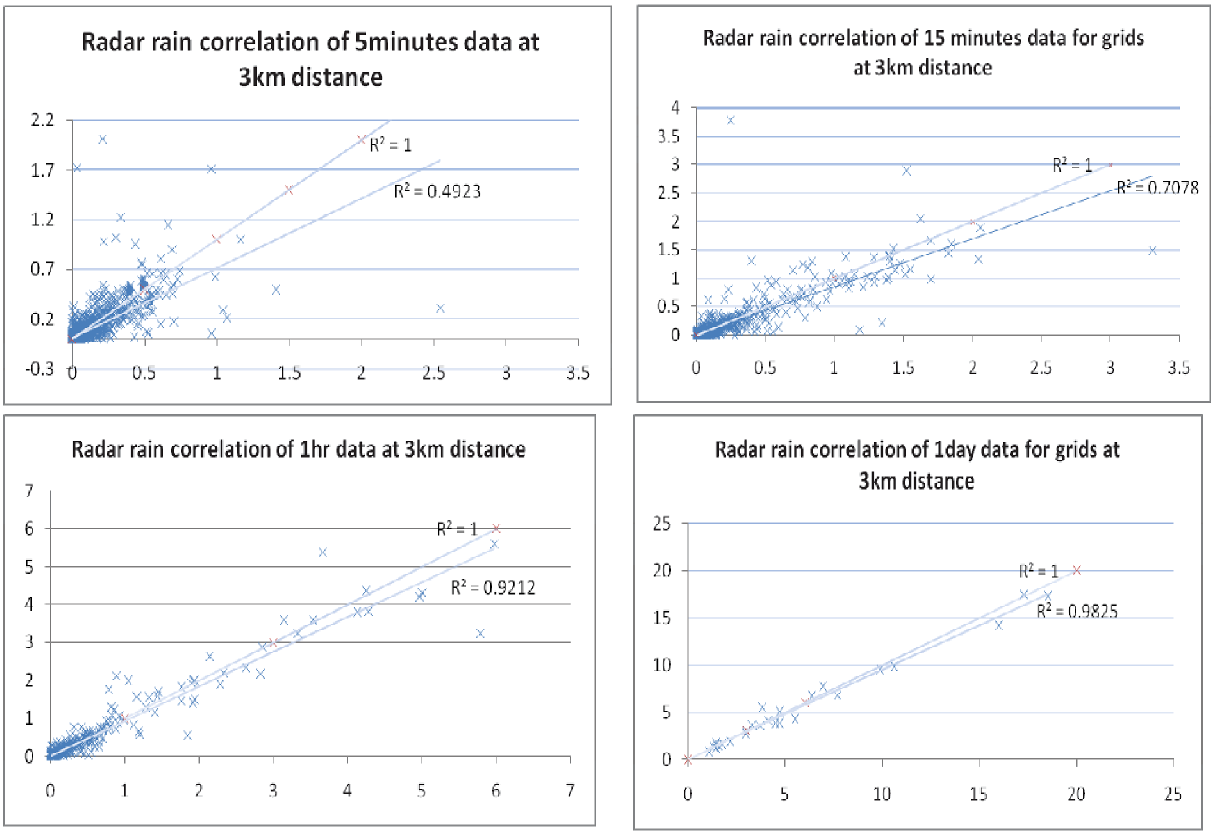


Figure 8.6 Radar Rain Correlation of 5minutes data for grid cells locaated at 3 km distance

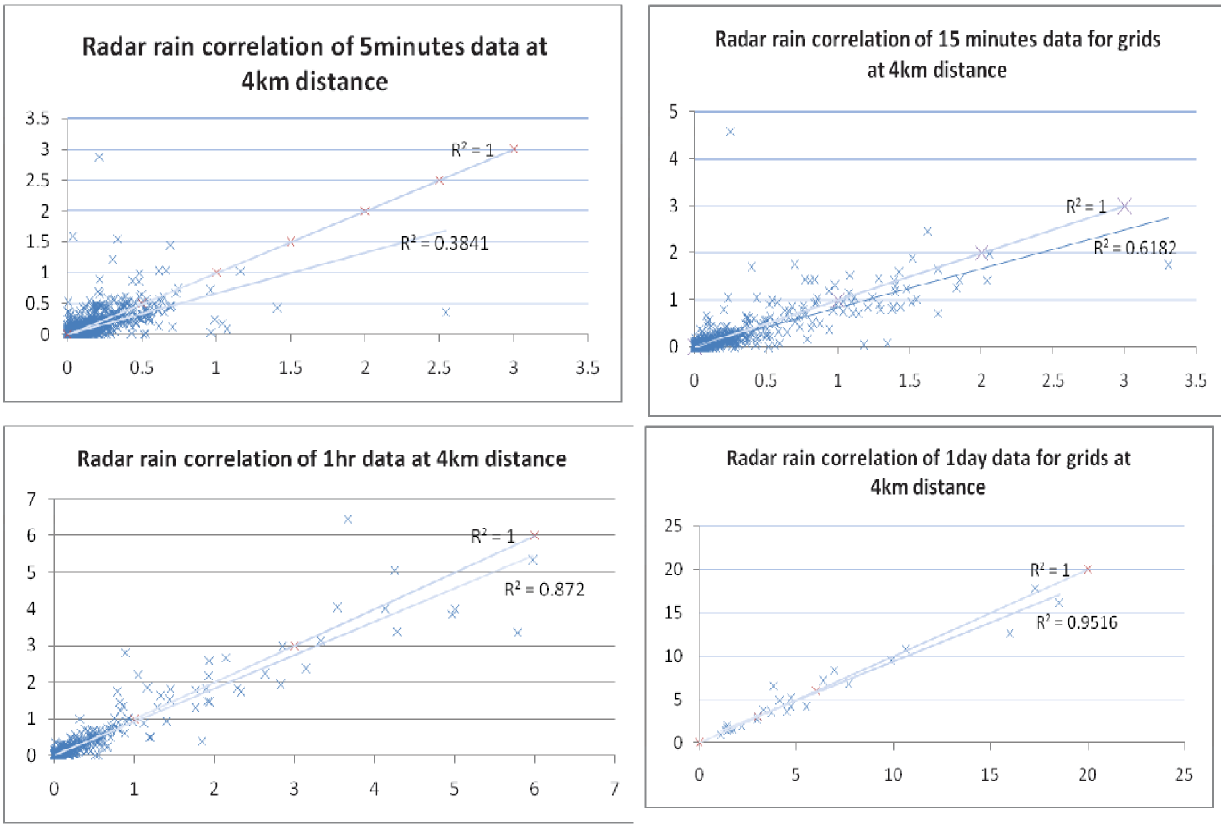


Figure 8.7 Radar Rain Correlation of 5minutes data for grid cells located at 4km distance

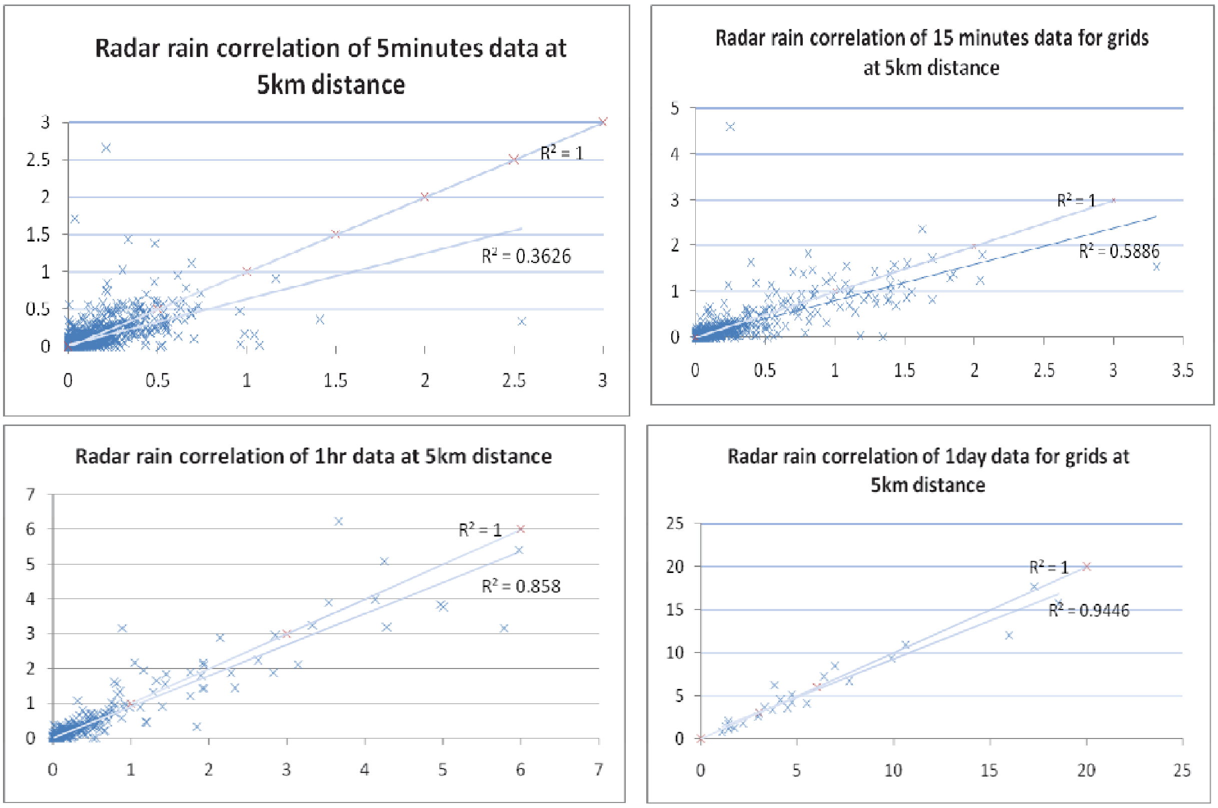


Figure 8.8 Radar Rain Correlation of 5minutes data for grid cells located at 5km distance

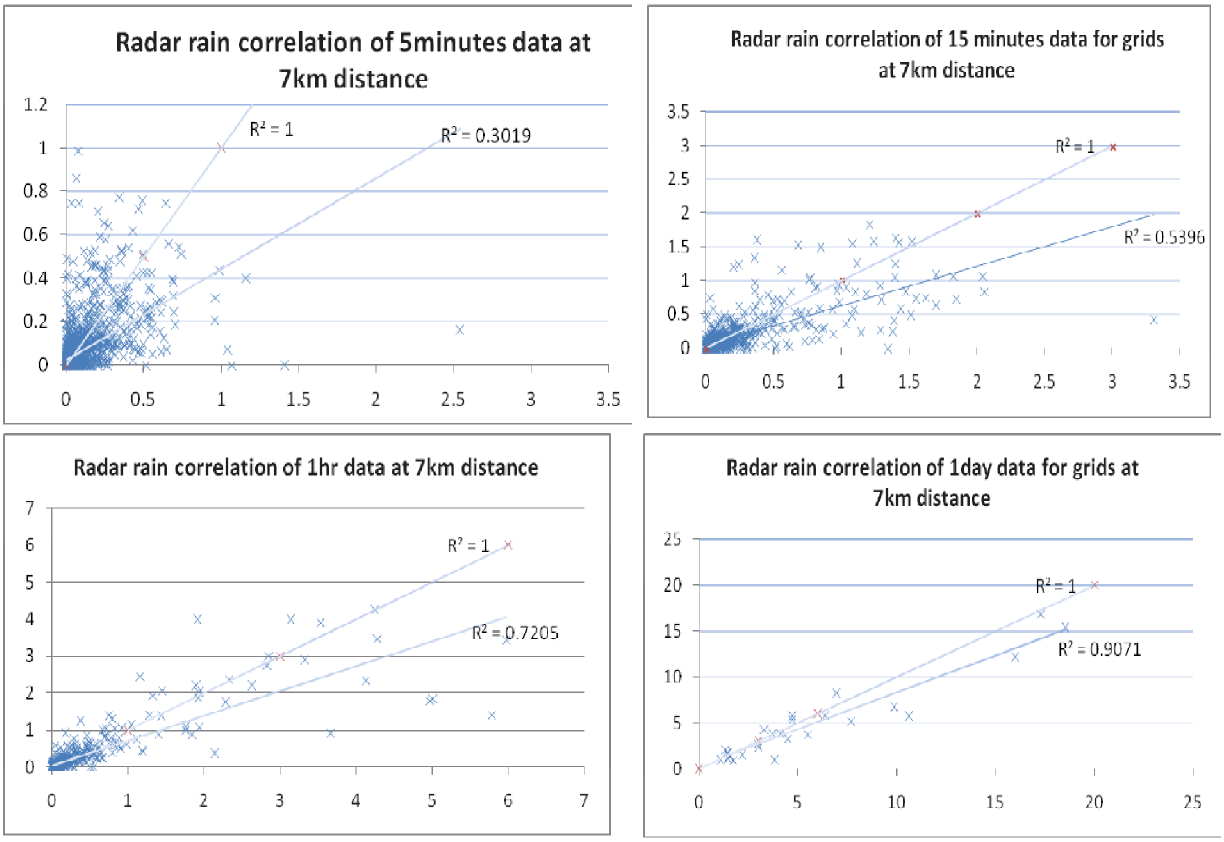


Figure 8.9 Radar Rain Correlation of 5minutes data for grid cells located at 7km distance

Result of the 5 minutes data analysis shows that values of correlation coefficient decrease as distances between grids increase; hence there is indeed variability in rainfall among grids with both time and space. Further analysis was made on these four different grids using regression analysis for time resolutions of 5 minutes, 1 hour and diurnal bases. The results of the analysis are shown in figures 8.10 to 8.13.

The daily rainfall variation across the grids in the research area are found to be negligible if all the rainfall ranges are considered as shown in figures 8.10 through figure 8.13. The correlation coefficient for daily rainfall is found to be close to unity. Further analysis was made to see the effect of small value rain events in this high correlation coefficient. Indeed these values have an effect as the correlation coefficient decrease when values above certain threshold are considered. Two threshold values (rain greater than 1mm and 2mm) were considered (by neglecting all the others values below the threshold in both cases). The correlation for 1mm threshold value is greater than that of the 2mm threshold value so this indicates that for big rain events there is diurnal variation too.

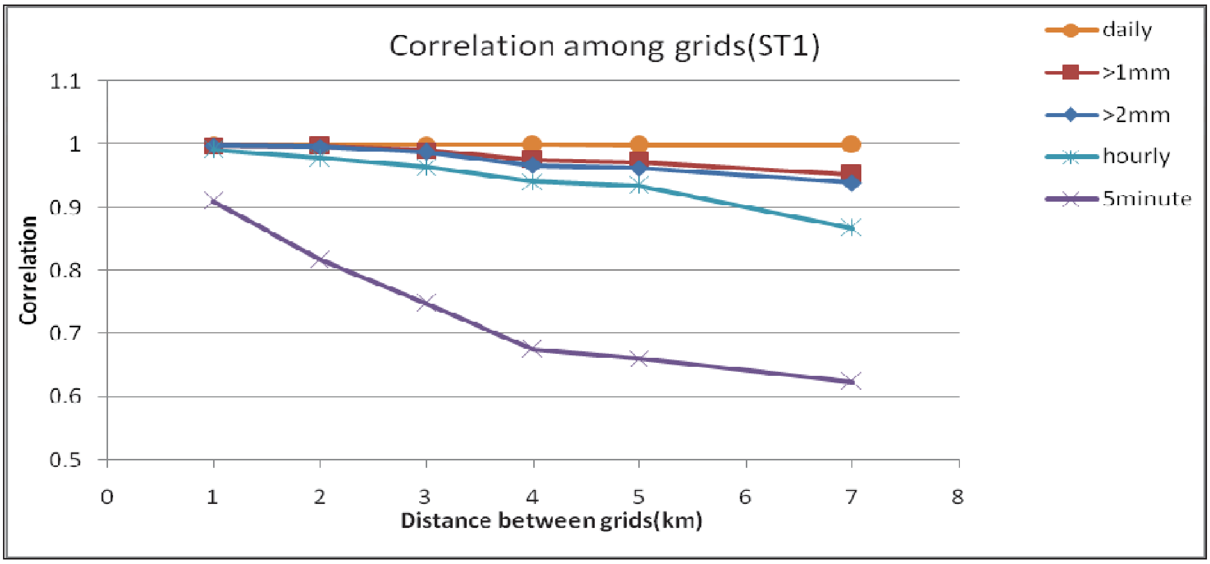


Figure 8.10 Correlation between ST1 and grids at distance of 1km to 7km from ST1

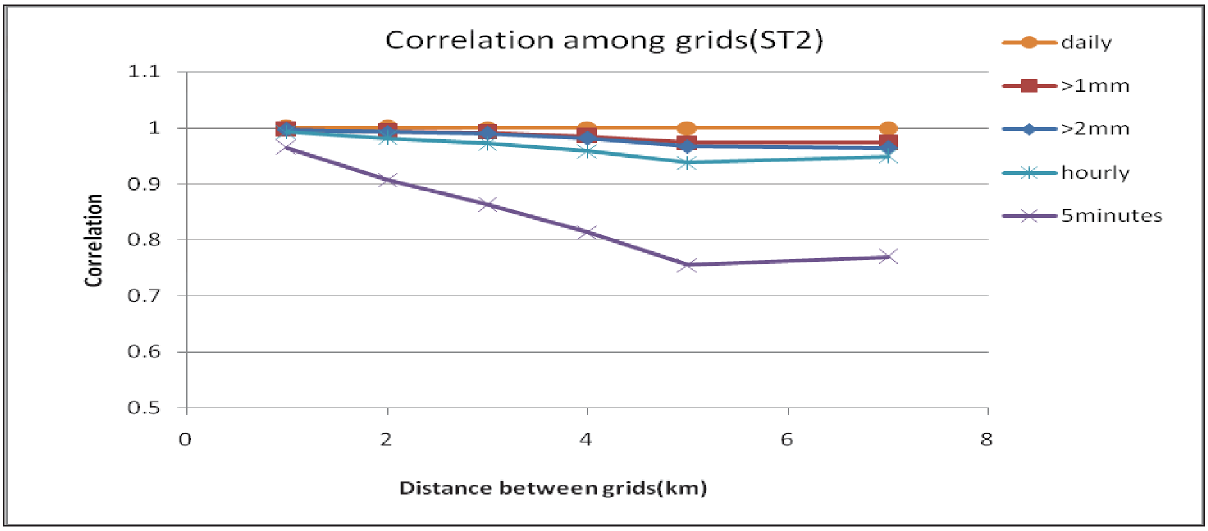


Figure 8.11 Correlation between ST2 and grids at distance of 1km to 7km from ST2

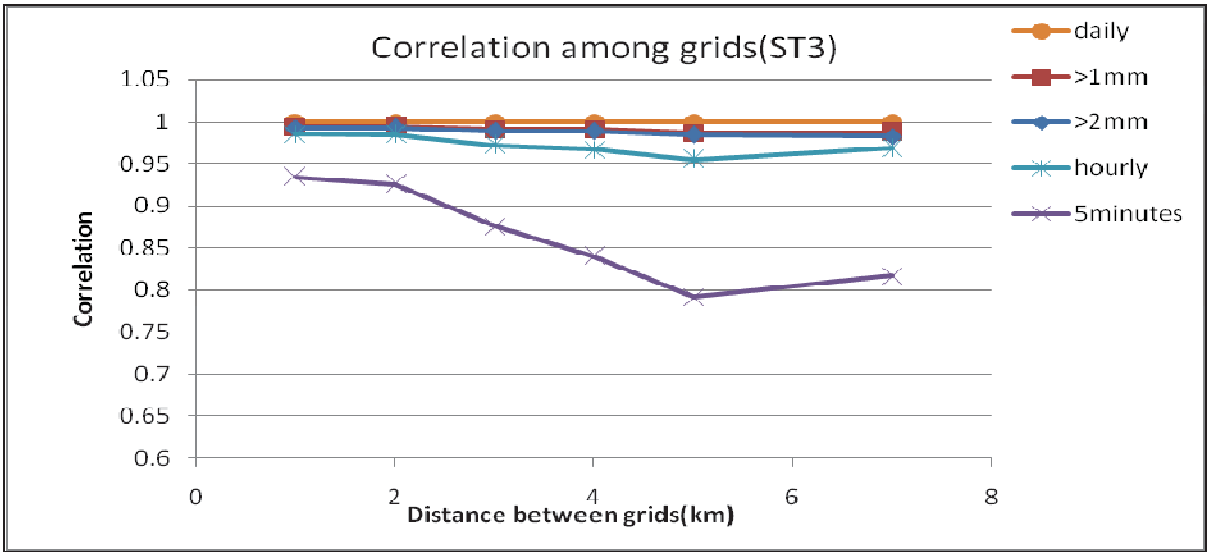


Figure 8.12 Correlation between ST3 and grids at distance of 1km to 7km from ST3

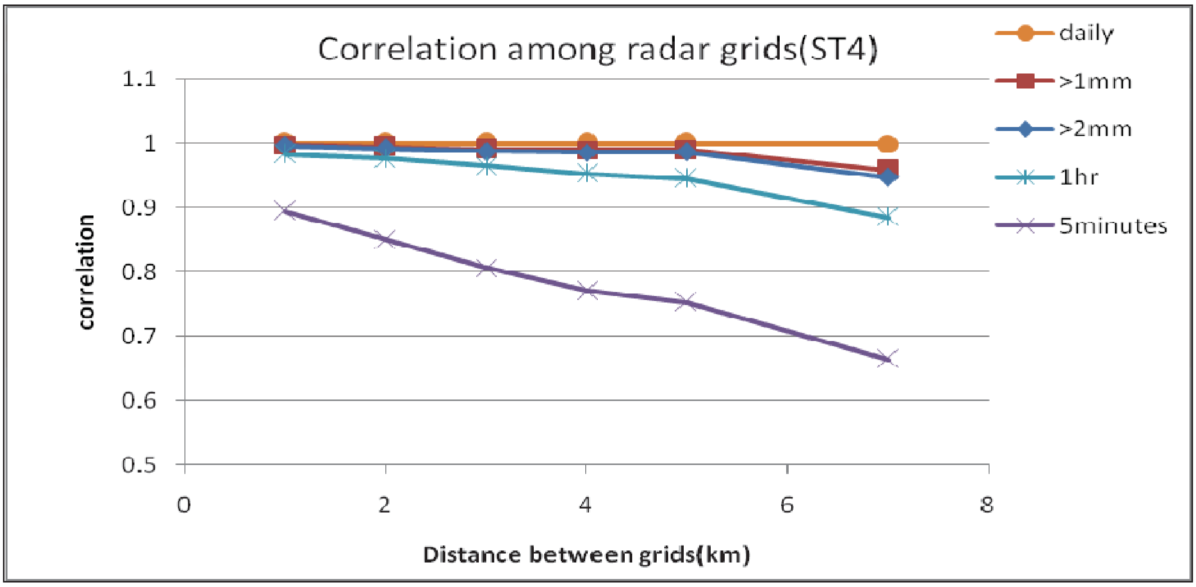


Figure 8.13 Correlation between ST4 and grids at distance of 1km to 7km from ST4

From the variability study of rainfall we have seen that there is variation of rainfall both in space and time. As we move farther from the grid the correlation coefficient is seen to decrease which is also the case when the time resolution increases. So in urban drainage systems where high temporal resolution is required it is not possible to get accurate data by interpolating among different rain gauges unless there is a dense rain gauge network to represent the spatial variation.

Analysis on data from two gage stations in Amersfoort (station 68 and station 89) is made to see the relationship between two rain gage stations. The distance between this two ground stations is 2.4 km and the analysis for 5 minutes, hourly and daily data sets is shown in figure 8.14 to figure 8.16 below. Data set used for this analysis is a four month 5 minutes data(December 2008-march 2009) measured at the corresponding stations and hourly and daily data sets are an aggregate of the 5 minute data sets.

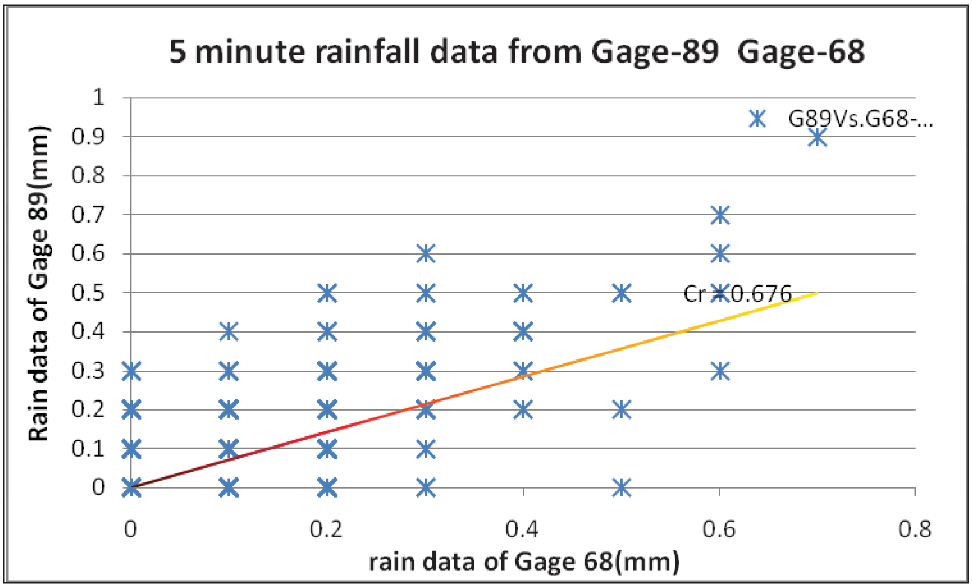


Figure 8.14 Correlation between 5minute data from rain gage stations located at 2.4km

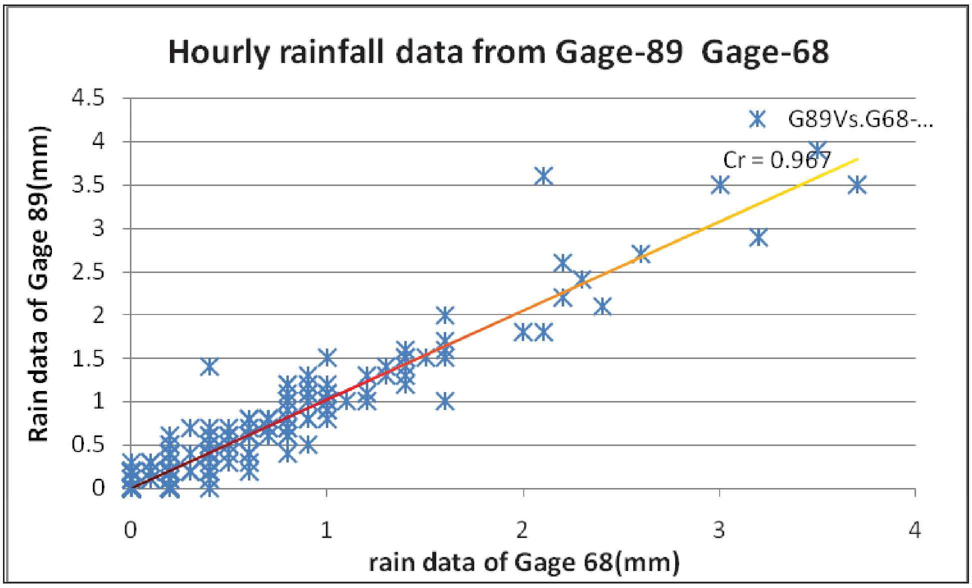


Figure 8.15 Correlation between hourly data from rain gage stations located at 2.4km

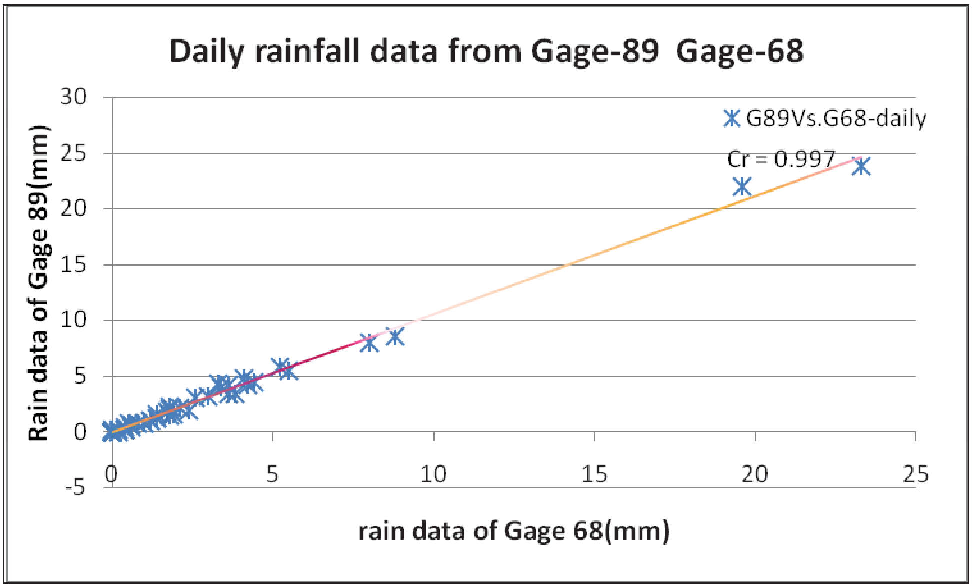


Figure 8.16 Correlation between daily data from rain gage stations located at 2.4km

From gage stations data comparison it can be seen from the correlation coefficient that the data sets have poor relationship. In radar grids comparison of the 5 minutes data the correlation coefficient observed for grids at a distance of 2.4km is above 0.8 which is better than 0.67 of the correlation coefficient for data sets from ground rain gage stations.

Next Radar -Rain and gauge- rain data sets are analyzed. Correlation coefficient of 5minutes, 1hour and 1 day data for gauges and grids corresponding to the rain gage are shown on figure 8.17 to figure 8.19. The 1hour and 1 day data are aggregate of the 5 minutes data set for both rain gage and radar data.

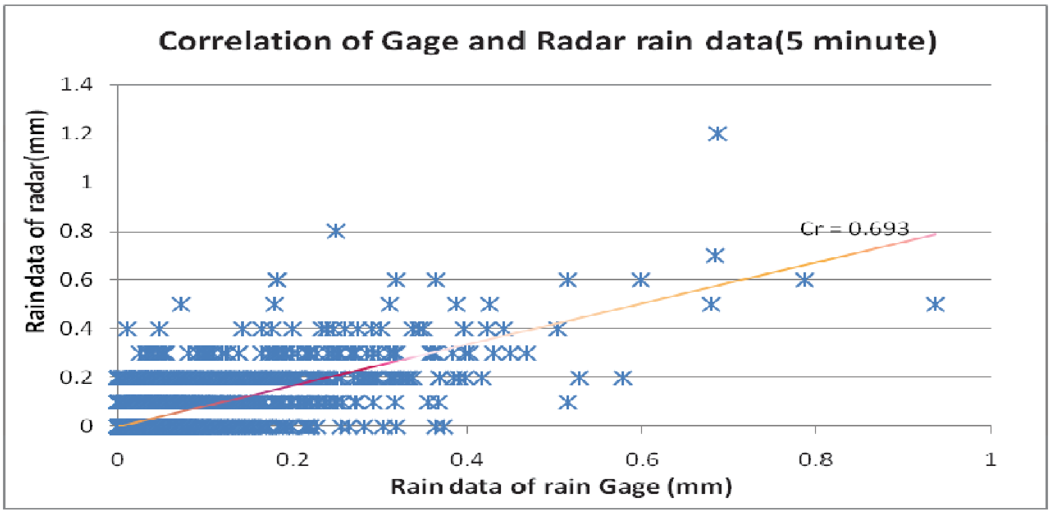


Figure 8.17 Radar rain and gauge rain data correlation of 5minutes data

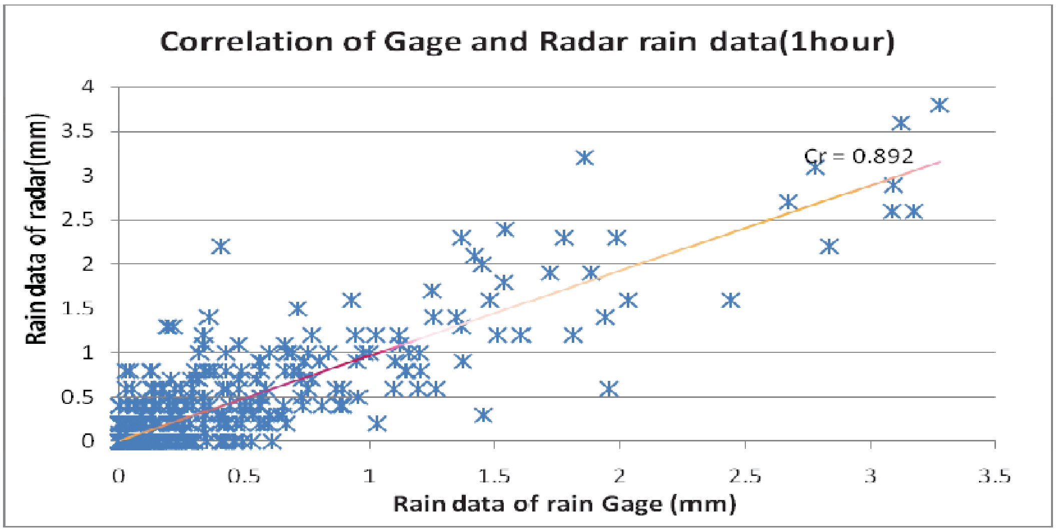


Figure 8.18 Radar rain and gauge rain data correlation of 1hour data

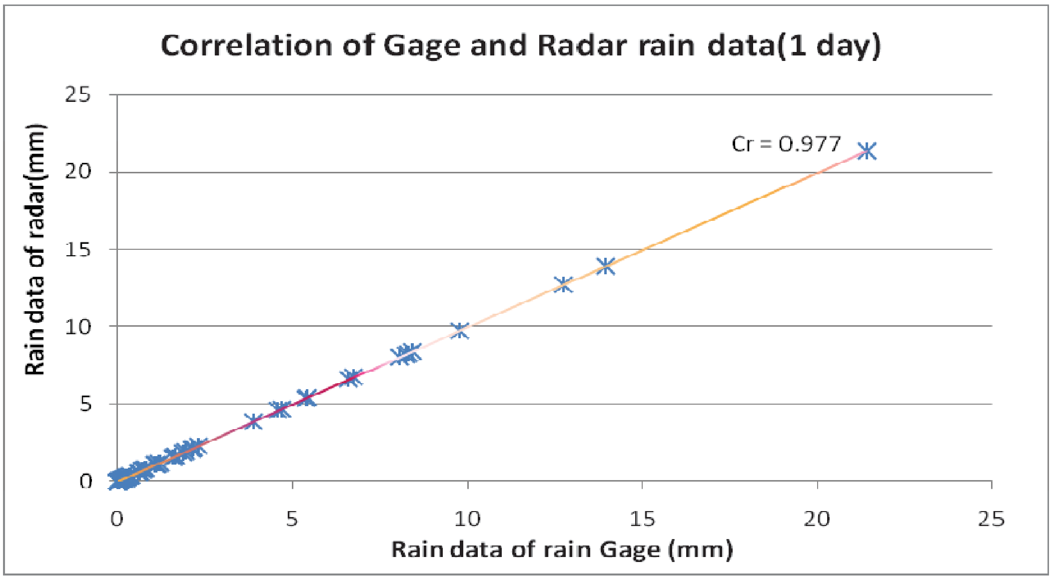


Figure 8.19 Radar rain and gauge rain data correlation of 1 day data

The relationship between radar measurement and ground measurement is shown to have a correlation of 0.693 for 5 minutes data and it keeps on increasing as cumulative rain of 1hr and 1 day is compared. The possible reason for this low correlation is that radar measurements are taken while the rain droplet is in the air. With an average fall velocity of 5m/s a rain droplet takes around 3minutes to reach the ground. A rain measured by the radar may not fall in the same grid due to effects of wind; it will blow the rain to the next grid so the amount of rain which is actually recorded by the radar for a specific grid may have variation with the amount of rain that reaches the ground and is measured by the rain gauge.

Further analysis is made to check correlation between data of consecutive time steps (data sets at time t and data set at time t+1) for each grid cell of radar and rain gauge. The result is presented in figure 8.20

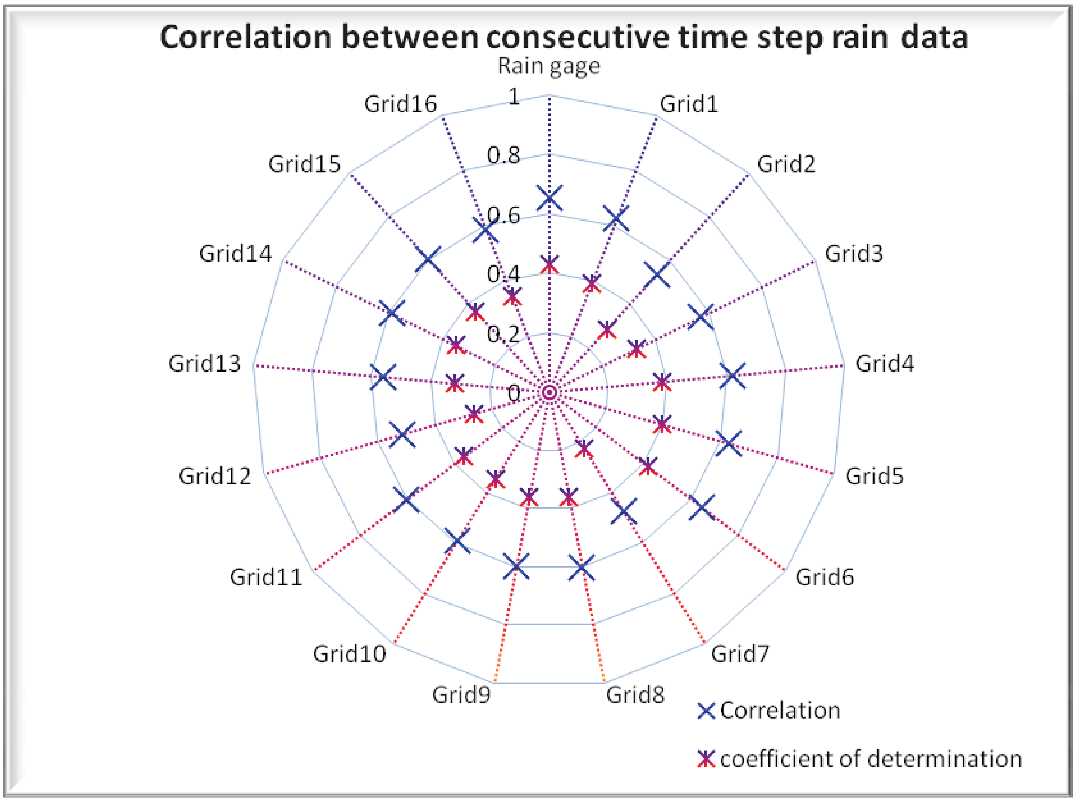


Figure 8.20 Correlation between consecutive time step data for both gauge and radar measurements

The result shows that coefficient of correlation for all the grids and the rain gage is around 0.6 and coefficient of determination of around 0.4. This shows that the relationship between consecutive rain measurements is low so measurements with small time step is important for getting accurate time distribution of rain fall.

From rainfall variability analysis it is found that rain fall have high spatial variability both in time and space. For small time interval between measurements rainfall variability is high and when the measurement interval increase variability decreases. Rainfall variability increases with distance between grids. This variability of rainfall data with distance and time interval between measurements for areas within the same climate is that movement of rain-clouds and rain droplets with wind.

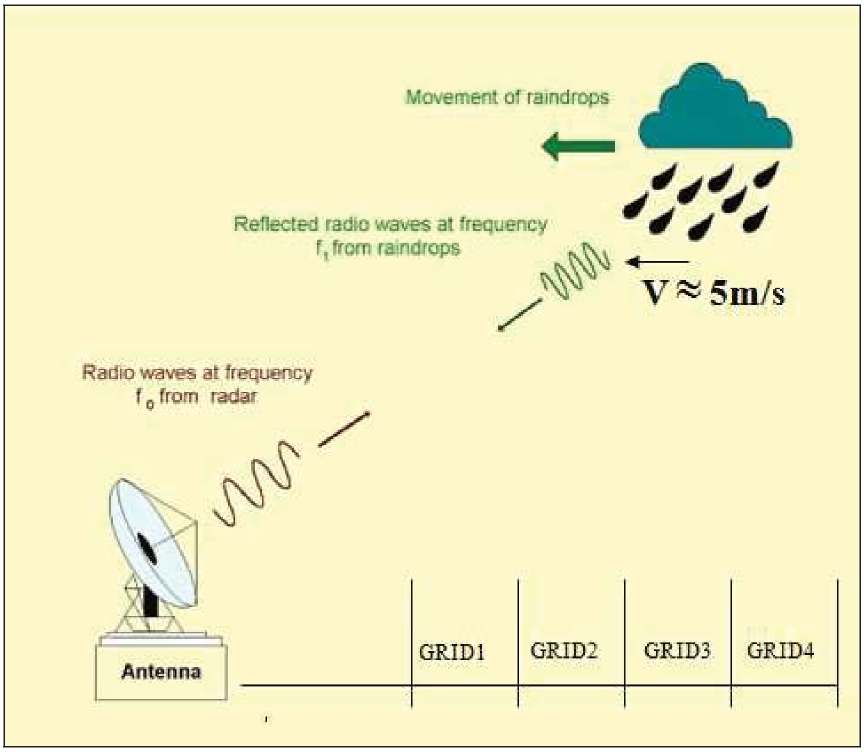


Figure 8.21 Effect of wind on rain droplets.

The average speed of wind in Amersfoort area is 3 m/s (source windkaart van Nederlands) and based on this wind speed travel time for rain droplet between two radar grids which are at a distance of 1km is around 5 minutes so this explain why rain data between two grids have high variability for small measuring time interval. But for large measuring time interval the cumulative rain falling over a certain area is more or less the same so the there will be less rainfall variability. Figure 8.21 shows the effect of wind on rain droplets.

The movement of rain droplets with cloud also explains the low relationship observed between radar rain data and ground station measurements. A rain droplet observed by the radar takes around 3 to 5 minutes to reach the ground and by then wind already blow it to another grid than it was originally observed by the radar therefore data measured by rain gage and radar will have poor relationship.

8.2 Solving Flooding problem

After running SWMM model for the design rain event some nodes indicate that there is flooding. Figure 8.22 shows the nodes with flood indicated with different colors depending on the extent of flooding

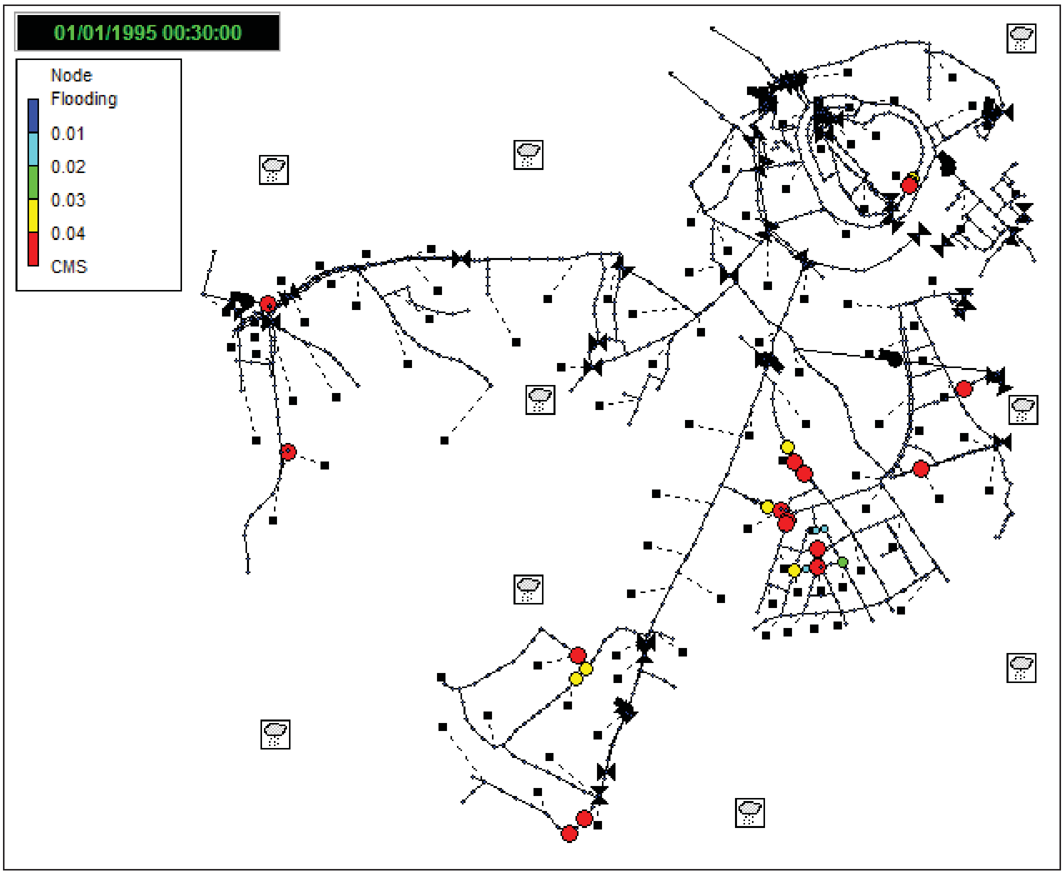


Figure 8.22 Flooding at different nodes due to design rain events

Figure 8.23 shows the profile of one pipe between two nodes with flooding. It can be seen that the hydraulic gradient is above the ground surface line hence some water on the surface.

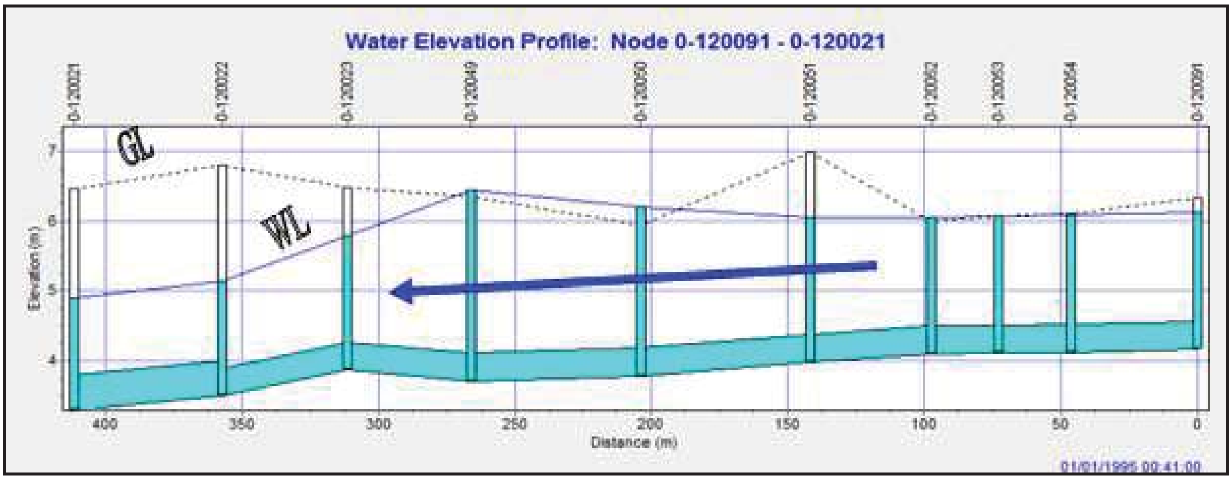


Figure 8.23 profile of pipe in flooded area

In order to solve this flooding (water-on-street) problem three alternatives are analyzed and the result will be explained next.

1. Hold the excess water in upstream pipes using control gates

All the pipes upstream and in the vicinity of the flooded nodes are checked for capacity utilization and figure 8.24 shows the result of this analysis. As it can be observed from the

figure the pipes were operating in full capacity for most of the simulation period so the first option is found to be inapplicable for this case

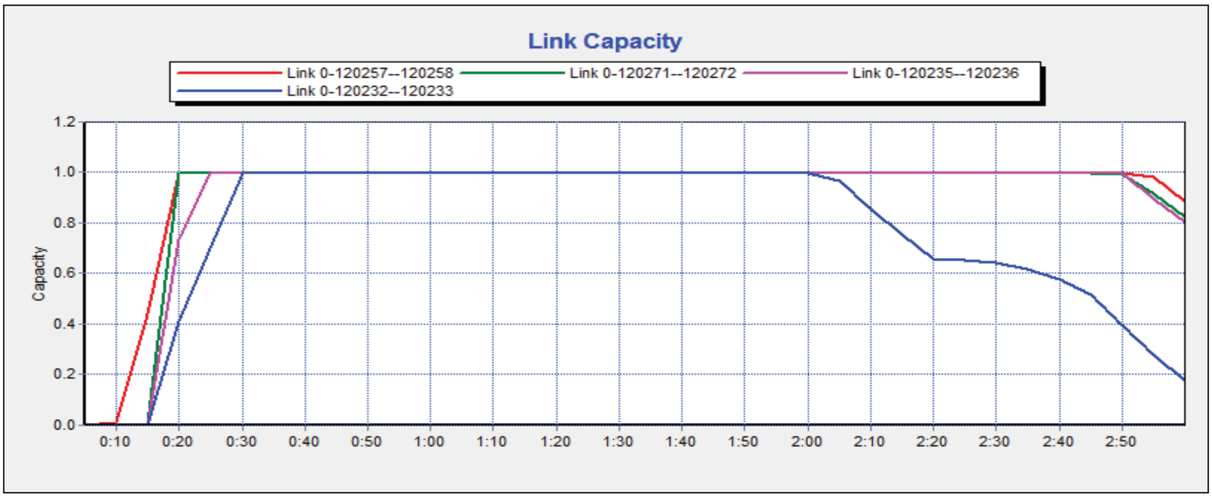


Figure 8.24 Pipe Capacity utilized during the simulation period

2. Divert the excess water to a node in another location using pump.

The drainage system in part of the city where there is water-on-street for design storm simulation has a maximum pipe diameter of 1000 mm while all the other pipes are of size between 400 mm and 700 mm. Pipe capacity utilization for this larger pipe, which is Pipe 0-70388-70390 in SWMM model, during the simulation period is shown in figure 8.25 together with two other pipes immediate downstream of it. From figure 8.25 it can be seen that the pipe is utilized to full capacity until one hour from the beginning of simulation and figure 8.26 shows the graph of flooding verses simulation time and flooding occurs during the first one hour of simulation. Therefore pumping to this location is not possible as there is no enough space to accommodate the excess water

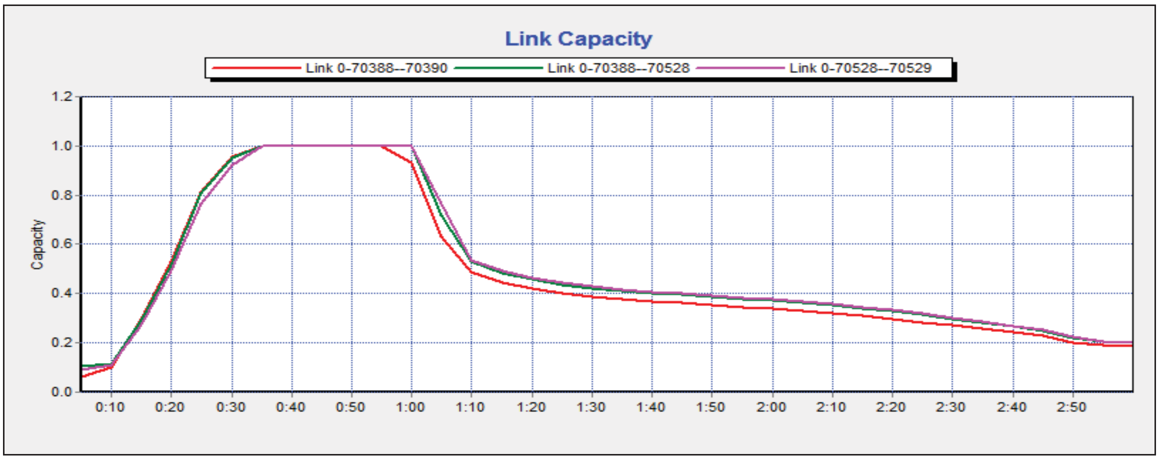


Figure 8.25 Pipe utilization capacity curve

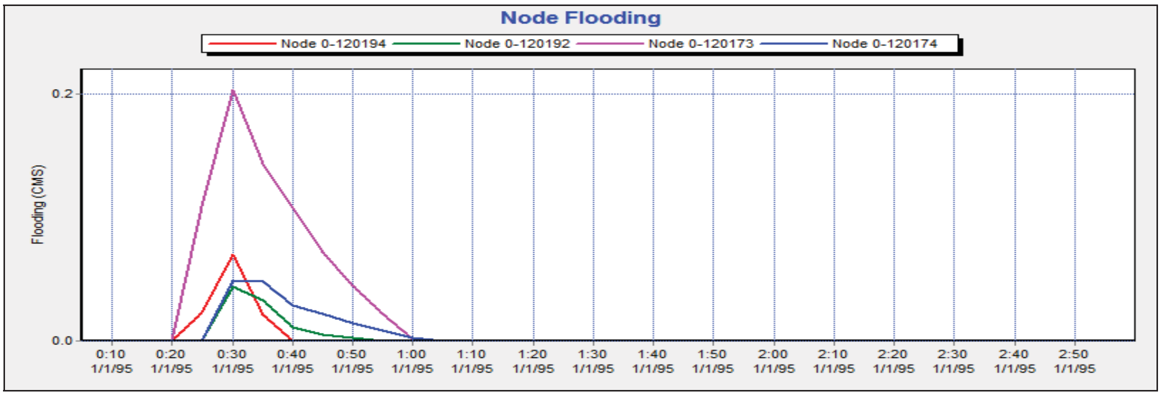


Figure 8.26 Flooding at nodes during simulation period

3. Implement a new offline storage tank

In the first two options if there were enough storage capacity to accommodate the excess rain water then the idea was to implement an RTC system which will distribute the excess water in the urban drainage system hence optimal use of the urban drainage system. But the options are found to be inappropriate to solve flooding problem as during peak flow all the pipes in the upstream of the flooded area are used to full capacity. To minimize flooding on streets during this rain event additional storages are required to hold the excess water at peak hour and release it back to the system after the peak hour. To determine the size of these storages Genetic algorithm is used, first the storage tanks are implemented in the SWMM model and in the GA analysis for each iteration different size storage tanks will be used and total surcharge volume will be calculated.

With storage volume and total flood as two objectives in GA with 20 generations and 20 populations in each generation the storage capacities are determined. Objective one is the total flood in the system and objective two is the sum of total storage volume expressed as the sum of length of storage one and storage two as the cross sectional area of the two storages is kept constant in the model and for each new run only the length will be adjusted to increase or decrease the storage volume.

$$obj[1] = Flood\_Volume$$

$$obj[2] = Total\_length\_of\_Storage\_Tanks$$

Flood volume is total volume of water surcharging from nodes and total length of the storage tanks is the summation of the two storages, the cross sectional area of the tanks is kept constant so volume will be a function of length. The boundary lengths in the GA analysis are 30m and 200m.

$$V = V_1 + V_2$$
$$L * A = L_1 * A + L_2 * A$$
$$L = L_1 + L_2$$

Figure 8.27 shows the best result for the last generation of the GA analysis.

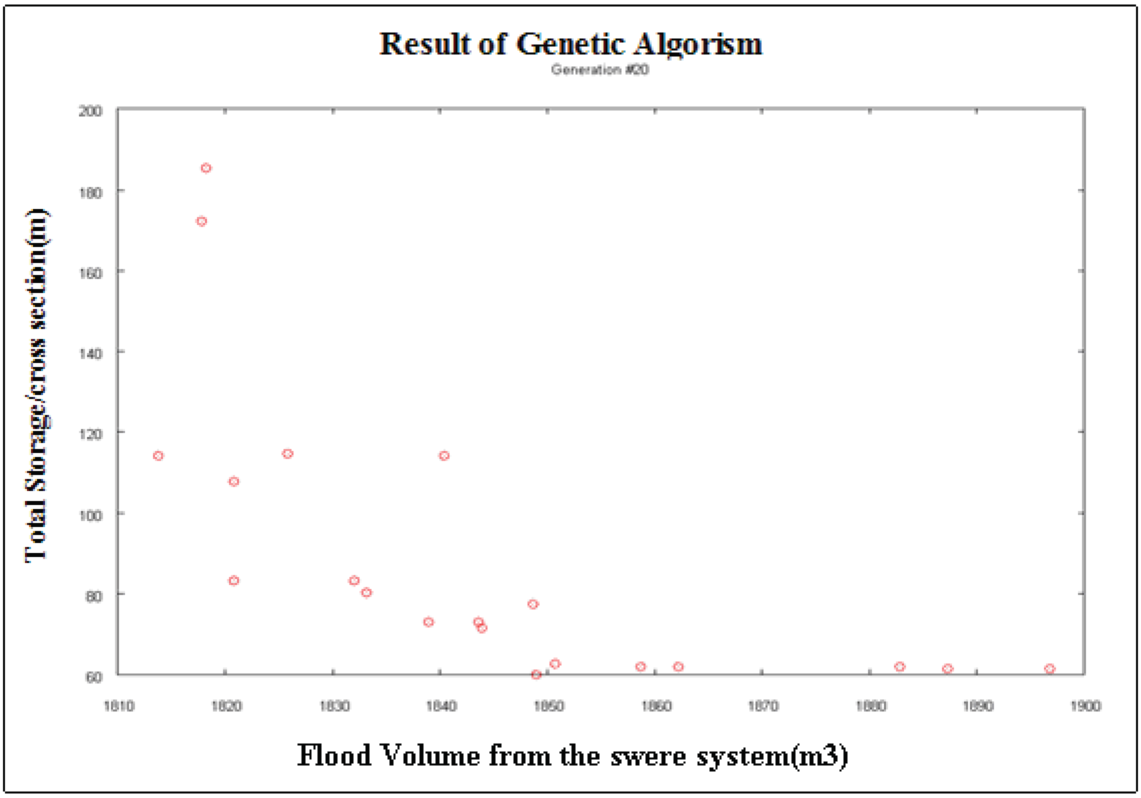


Figure 8.27 Result of 20th generation GA for storage and total flood.

Table 8.1 Best result for GA for flooding and storage

Objective 1 (Total Flood)	Objective 2 (Total Length)	Length 1 (volume/area)	Length 2 (volume/area)
1848.97	60.05	30.03	30.02
1843.89	71.70	41.64	30.06
1820.86	83.11	53.05	30.06
1820.82	107.66	55.60	52.06
1813.82	114.28	56.14	58.15
1838.92	73.12	43.07	30.06
1833.13	80.19	50.19	30.00

Note:- application of GA here is just to solve the searching problem, which is to find the size of storage tanks to accommodate the excess water during design storm so that there will be no flooding and CSO problem. And best solution in table 8.1 means storage size corresponding to the least flooding volume.

So based on the GA analysis the best solution is one which minimize objective one (total volume of flooding calculated from surcharge volume), and this point can be selected from figure 8.27 or table 8.1.

Based on result of GA for storage dimensions two storages are implemented in the SWMM model and after running the new model the flooding (water-on-street) problem is solved as it can be seen from figure 8.28. Some nodes are still colored after solving flooding at specific location but this is not real flooding; the model is simplified by eliminating some pipes and

feeding all the rain in the specified area to a single node and this causes flooding on those nodes. Figure 8.29 shows the profile with the same pipes as that of figure 8.23 but here after solving the flooding problem. The hydraulic gradient line is below the ground surface for all the nodes which means there is no flooding.

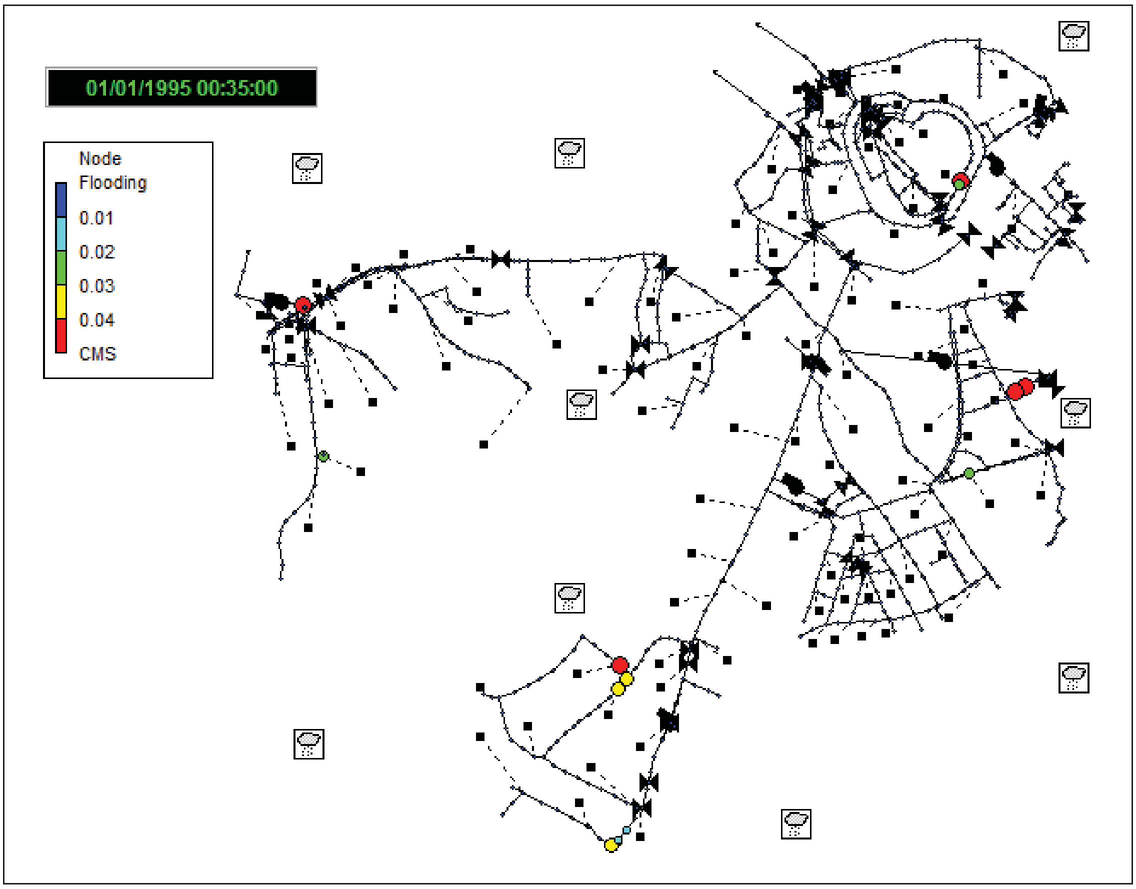


Figure 8.28 Networks lay out after floods at nodes solved using alternative three.

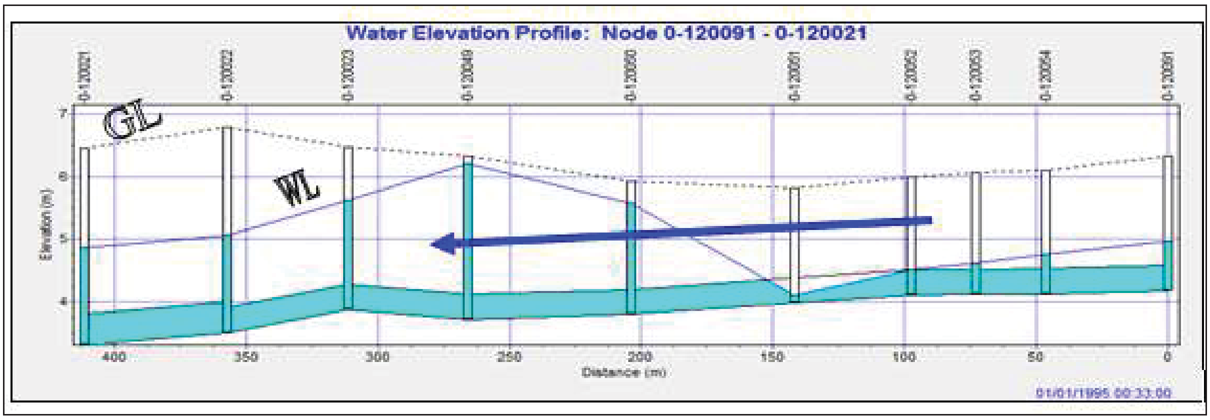


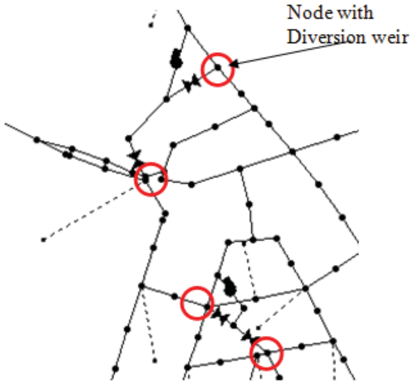
Figure 8.29 Profile of pipe after flooding problem is solved

8.3 Application of RTC for optimized usage of the storage tanks

In section 8.2 the optimal storage volume for the design storm to solve flooding problem has been implemented in SWMM model and after running the model the result shows that flooding problem is solved. If this storage volume is implemented online in the urban drainage system storm water will flow into the storages even for small rain events while the

system could accommodate the storm water with out any flooding. Here application of RTC system for optimal usage of the storage facility for any rainfall event will be evaluated. As pumping the water back to the system from storage tanks involves cost optimal usage of the storage will be to allow only part of the peak flow which may cause flooding into the tank and this can be achieved by implementing controlling crest level of weirs diverting storm water into storage facilities. With application of RTC it is possible to make an urban design system work optimally as otherwise it is optimal only for the design event loading (W.Schilling et al., 1989)

The two objectives are to reduce flood on streets, which is a primary objective, and minimize the amount of water going into the offline storage facilities to minimize operation cost. Forecast rain data is available from KNMI with two hour lead time which will be used as an input in the SWMM model. Weir diverting storm water into these storage facilities have a movable crest level. In the process of optimization SWMM model will run in iteration loop and for each run crest levels will be changing starting from level same as street level, so that no water will enter into the storages, to a level 40 cm above the bottom of the manhole lowering the crest level by 10cm for each run. In figure 8.30 nodes with diversion weir and detail for one location is indicated.



Nodes with diversion weir are indicated by circle on this figure and detail is shown in the right for one node.

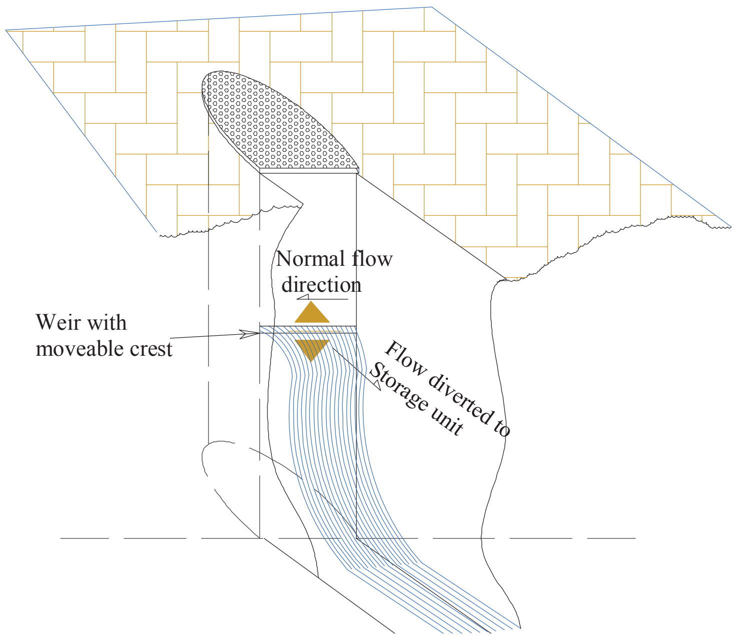


Figure 8.30 Nodes with diversion weir and detail section of one weir

After each run flood volume is calculated, table.8.2 shows the crest level vs. flood volume for the design storm and is plotted as shown in figure 8.30. From the result it is observed that flood volume decreases up to crest level of 1.3 m and is then constant though weir level is lowered further. This is because in the model there are nodes with false flooding: the model is simplified by removing pipes so the storage volume available in the model is less than the actual volume available in the pipe network therefore at nodes which are outlet for sub-catchments the model indicate flood but actually runoff from sub-catchments enter into the pipe network through different manholes which are in the urban drainage system. The constant flood value in figure 8.31 is the summation of false floods indicated in the SWMM model.

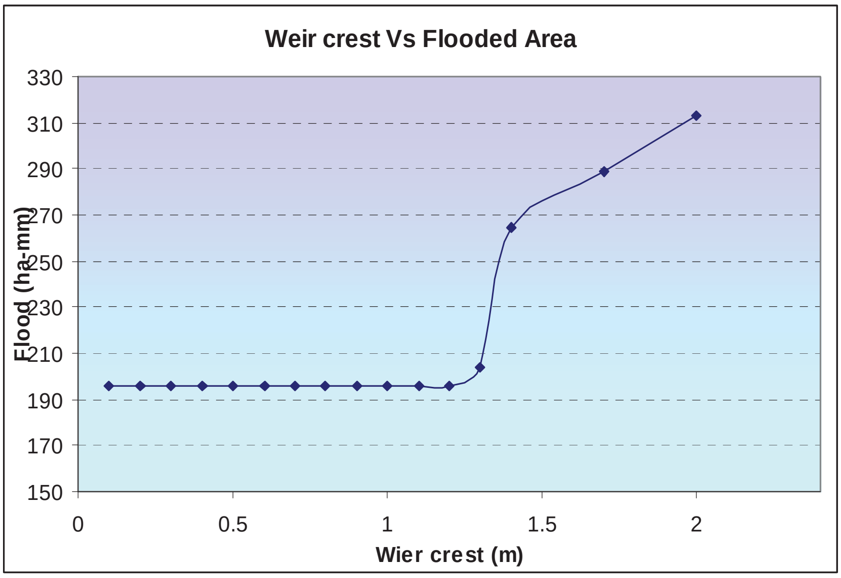


Figure 8.31 Total flooding and weir crest level

Table 8.2 Crest level Vs flood volume

Crest Level (m)	1.7	1.4	1.3	1.2	1.1	1.0	0.9	0.8	.7
Flood Volume (m^3)	313	289	264	203	195	195	195	195	195

8.4 Web pages

The web pages are the final and important part of the demonstrator to convey the simulated information using real time radar rain data. The web page includes home page and pages showing plots of water depth at nodes, over flow locations and storage capacity utilization of storage facilities. Rain fall data used in the simulation model is also plotted in the same page showing simulation results. The screen shot of the main page is shown in figure 8.32, a user will navigate to the page of each nodes, CSO locations and storage facilities by clicking the link on the markers. These markers are placed on Google map based on the actual geographical locations of manhole, CSO location or storage facility. Screen shot of pages for CSO, water depth at manhole and % utilized capacity of storage facilities are shown in figure 8.33 through figure 8.35

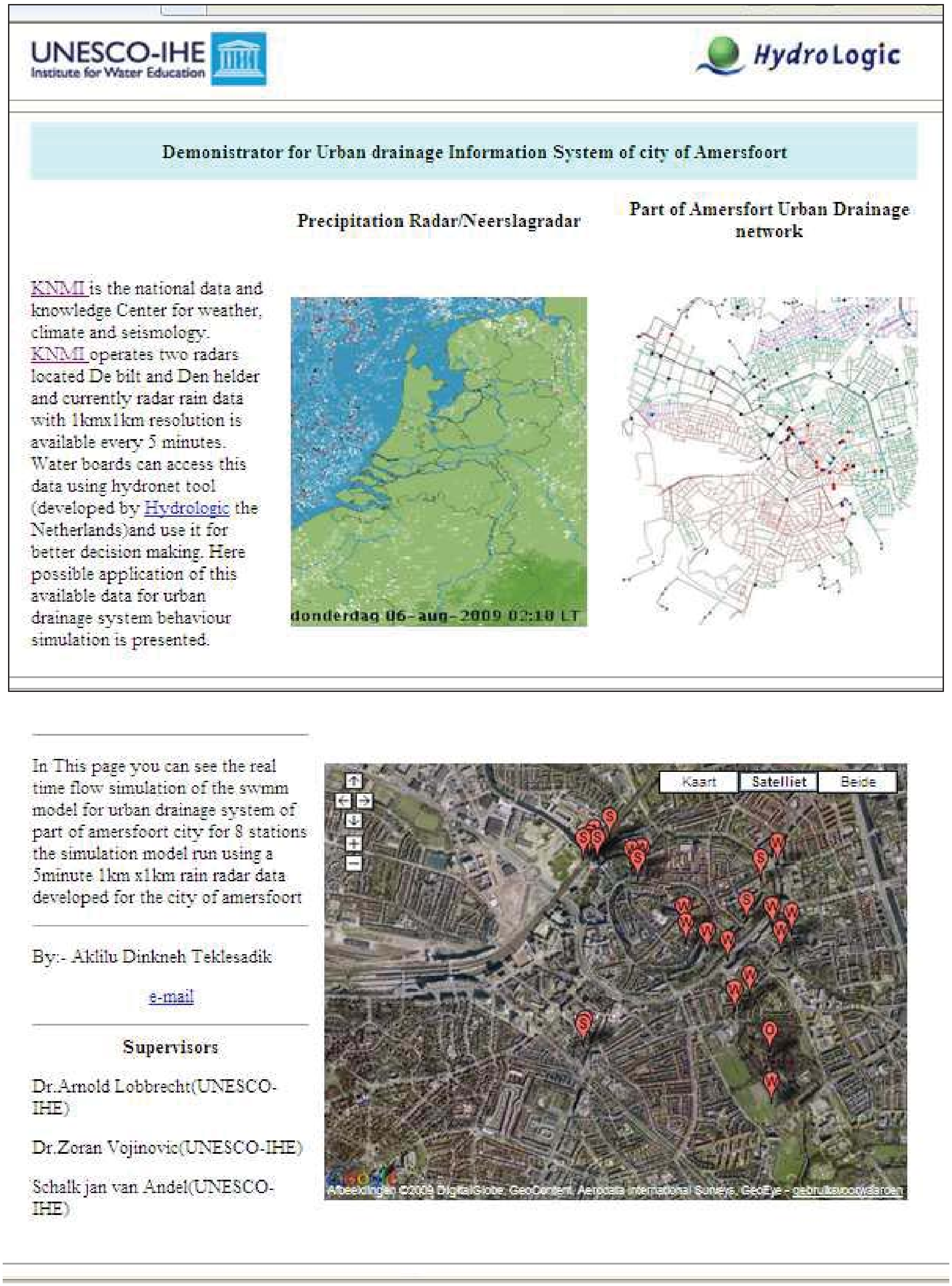


Figure 8.32 Home page of the web site

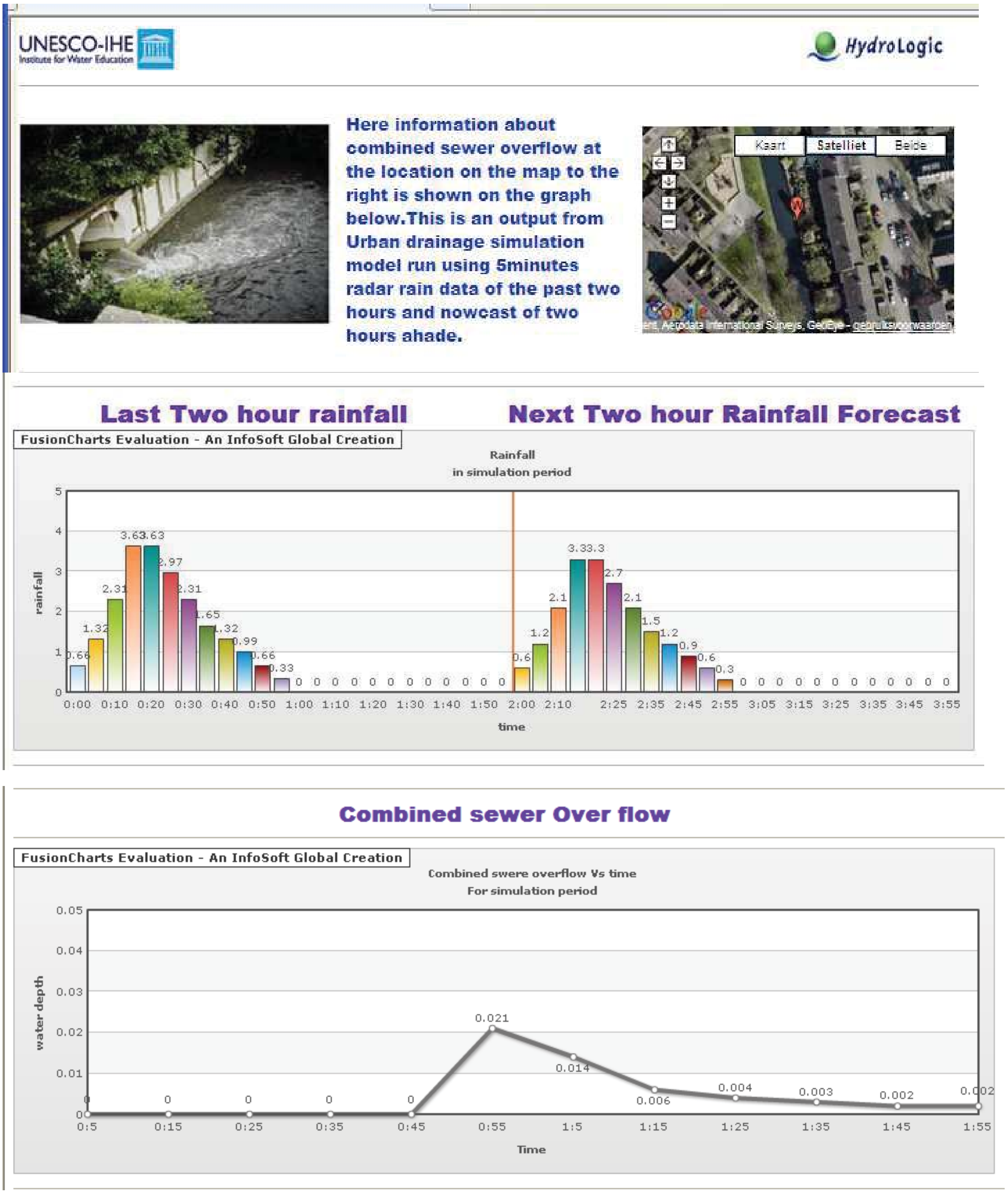


Figure 8.33 screen shot of page showing result of CSO

In figure 8.33 rate of flow vs. time of SWMM simulation is displayed for one combined sewer overflow location. The rain event used as input in the SWMM model, which is the design storm in this case, is also displayed in the same page.

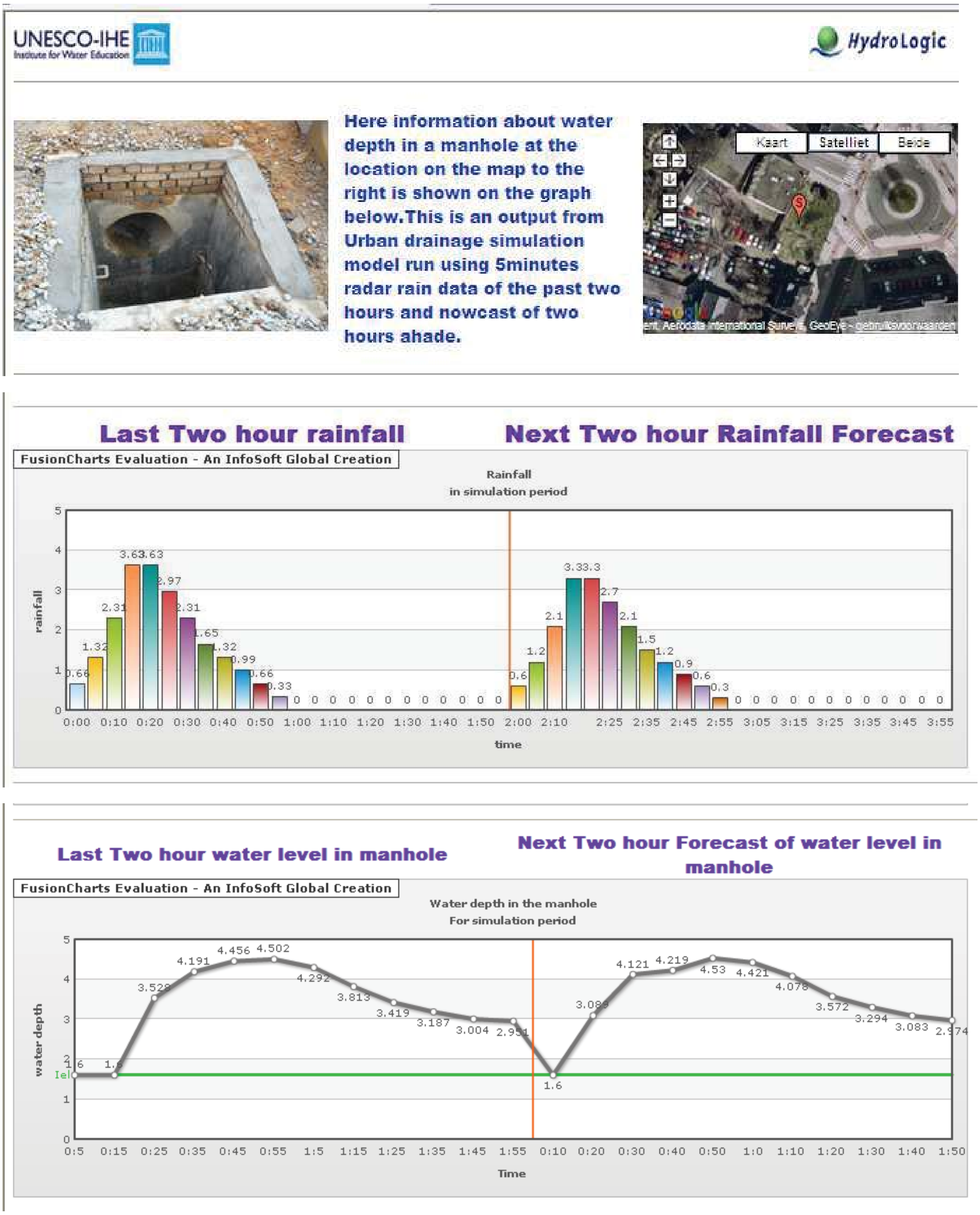


Figure 8.34 screen shot of page showing water level in manholes

In figure 8.34 water level at a manhole for the simulation period is depicted. The invert elevation and street or ground level are shown in the graph but in this case as the water level in the manhole is far below the ground there is no flooding at this node.

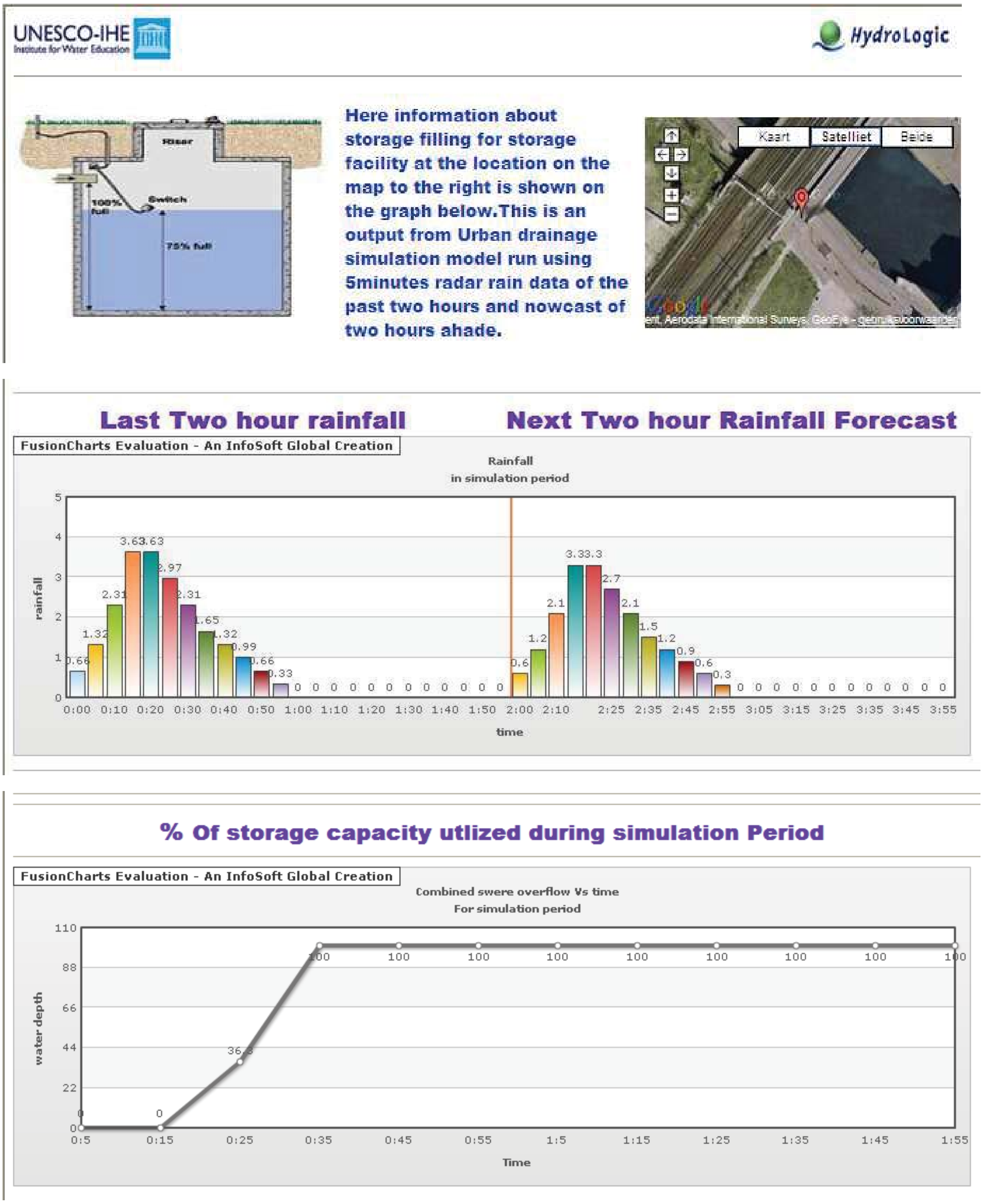


Figure 8.35 shot of pages showing % utilized capacity of storage facilities

Figure 8.35 shows the percentage utilization of one of the storages in the system and it can be seen from the figure that the storage is filled gradually in the simulation period. If the rain event continues after storage tanks are filled flooding or CSO could occur somewhere in the system.

9. CONCLUSIONS

The following conclusions are reached based on the analysis done using case study of the city of Amersfoort to achieve the objective of the thesis.

- An online information system which presents results from real time urban drainage simulation model using high resolution real time radar rain data is developed. The demonstrator provides information like rate of flow in CSO locations, water level at nodes and percentage of utilization of storage tanks for recent and forecasted rain event. Synthetic data is used to simulate results for rain forecast as web services to access rain forecast data on real time is not currently available. This information could be useful for analyzing the performance of the urban drainage system in real time during different rain events.

- From rainfall variability analysis it is found that rainfall has high variability both in time and space. For small time interval between measurements rainfall variability is high and when the measurement interval increase variability decreases. In addition to the non homogenous nature of rainfall this variability with distance and time interval between measurements for areas within short distance is because of movement of rain-clouds and rain droplets with wind. So measurements with high spatial resolution and small time step are important to get data representing the real situation. Radar measures rainfall with higher spatial resolution than sparsely distributed rain gage networks. From the case study 1 km x 1 km grid and 5 minutes time step radar data available from KNMI express rainfall variability better than sparsely distributed rain gage network and is useful to get data representing the real situation of rainfall distribution. This have important application in urban areas where sub-catchments have fast response for rainfall and therefore models require data with high spatial and temporal resolution

- Based on the SWMM modelling analysis of performance of the urban drainage system of city of Amersfoort for design storm there is a flooding problem at the bottom of the hilly area. In order to this flooding problem additional storage facilities are required as the drainage system capacity is fully utilized when flooding occur during design storm. However, these storages are going to be used optimally only for one rain event which is the design storm. For a rain event less than the design storm it is not required to fill storages facilities fully so by diverting only portion of storm water which could cause flooding into the storage facilities energy required to pump the water back into the system could be minimized.

- For an economical operation of the proposed storage facilities to solve flooding problem a proactive RTC system is evaluated. A diversion weir with controlled crest level is implemented in the model. For a rain event the RTC system will run SWMM model in iteration loop to fix the optimal crest level which allows only part of the excess storm water which may cause flooding and CSO problem into the storage tank and latter after the peak flood pumping the water back into the system. Based on result of the analysis made on the SWMM model loaded with different rain events application of proactive RTC together with storage facilities in the urban drainage system of the city of Amersfoort will solve flooding problems in an optimal way from

an operation cost point of view (energy cost for pumping the water back into the system will be optimized by diverting only part of the storm water which may cause flooding and CSO problem).

10. RECOMMENDATIONS

Based on the analysis made in this research the following points are recommended to improve the developed demonstrator and urban drainage system management in Amersfoort

- For this demonstrator files were used for data storage by over writing every time the system runs and update data but if data base system like MySQL is applied it will be possible to store historical data hence more informative system and easy to evaluate performance of the simulation model in comparison with measured data over longer period.
- In the demonstrator part it was mentioned as an objective to present real time measurements in the urban drainage system together with SWMM simulated results in the web pages but for this research it was not possible to include measured data in the web pages because web services to access database of the measured data is not available. If measured data is included in the web page reliability of the information from SWMM model simulation will be more and when ever there is a big deviation between measured and simulated values the model could be further calibrated and validated accordingly.
- Data for calibration was difficult to get which is very important to improve the quality of the model so the model should be further calibrated with available data from the measuring stations.
- Data measurement in the sewer system is taken only from measuring stations located at either pumping stations or storage basins and these measurements are water levels in storage basins. For model calibration it is better to have data like flow rate and water level in sewer pipes. Establishing new measurement stations to collect these types of data will robust the SWMM model means better simulation of the urban drainage system.
- SWMM does not compute overland flow: it stores precipitation in a reservoir and discharges it to an outlet. This flow is schematized by flow in a wide rectangular channel according to Manning's equation, where flow width is specified by the width parameter and height is the ponded water depth. So flow metering data from sub-catchments in the watershed should be used for calibration to adjust the characteristic width parameter until a good fit exists between the observed and simulated discharge hydrographs. This will make the SWMM model more robust
- To solve flooding problem in the city of Amersfoort building additional offline storages at flooding location is better solution as for the design event the drainage system capacity is fully utilized. For optimal use of these storage facilities proactive RTC system can be implemented using high resolution rainfall forecast data available from KNMI.

11. REFERENCES

Akan, A.O., 1993. Urban Stormwater Hydrology: A guid to Engineering Calculations.

Anagnostou, E.N. and Krajewski, W.F., 1999. Real-Time Radar Rainfall Estimation. Part I: Algorithm Formulation. Journal of Atmospheric and Oceanic Technology, 16(2): 189-197.

Australia-Bureau-of-Meteorology, 2009. How Radar Works. In: B.o. Meteorology (Editor). Bureau of Meteorology

Bernea, A., Delrieub, G., Creutinb, J.-D. and Obledb, C., 2004. Temporal and spatial resolution of rainfall measurements required for urban hydrology. Journal of Hydrology, 299: 166-179.

Brockies, J., 2009. North Shore City Council's Infrastructure Design Standards Manual.

Butler, D. and Schütze, M., 2005. Integrating simulation models with a view to optimal control of urban wastewater systems. Environmental Modelling & Software, 20(4): 415-426.

C James, W.R., Heralall, M. and James, W., 2008. Integrated web-based automated radar acquisition, processing and real-time modeling for flow/flood forecasting, 11th international conference on urban drainage, Edinburgh, Scotland, UK.

Davis, L.D., Mitchell, M. and Reinhold, V.N., 1991. Handbook of Genetic Algorithms.

Desa, M.M.N. and Niemczynowicz, J., 1996. Spatial variability of rainfall in Kuala Lumpur, Malaysia: long and short term characteristics. Hydrological Sciences, 41(3).

DHI, Locall Arrea Weattherr Radarr -- LAWR a Prroductt ffrrom DHII Weattherr Radarr Systtems.

English-Heritage, 2003. Coastal Defence and The Historic Enviroment.

Geerse, J.M.U. and Lobbrecht, A.H., 2002. Assessing the performance of urban drainage systems: ‘general approach' applied to the city of Rotterdam. Urban Water 4: 199-209.

Gemeente-Amersfoort, 2008. Beschrijving van het gemeentelijk rioleringsbeleid in Amersfoort voor de periode 2007 t/m 2011, Amersfoort.

Goormans, T. and Willems, P., 2008. Correcting rain gauge measurements for caliberation of an X-band weather radar, 11th international conference on urban drainage, Edinburgh, Scotland, UK.

Gorgucci, E., Scarchilli, G. and Chandrasekar, V., 1996. Error structure of radar rainfall measurement at C-band
frequencies with dual polarization algorithm
for attenuation correction. Journal Of Geophysical Reserch, 101: 461-471.

Grecu, M. and Krajewski, W.F., 2000. Rainfall forecasting using variational assimilation of radar data in numerical cloud models. Advances in Water resources, 24(2): 213-224.

Gupta, K., 2007. Strategies for Integrated Urban Drainage Management In Monson Rainfall Areas With Special Reference to The Indian Subcontinent, The UNESCO International Symposium on New Directions in Urban Water Management,, Paris.

Hanson, D.S. and Edwards, G., 2008. Integration of rainfall radar into real-time information system, 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK.

Holleman, I., 2009. Introduction to Radar http://www.knmi.nl/~holleman/.

Hoogeveen, D., 1990. The Use of Water Level predictions in Real-Time controlled Polder System, Application of Operations Research to Real Time Control of water Resources Systems, Kastanienbaum/Luzern,Switzerlannd.

Huber, B., Rabsamen, U. and Schilling, W., 1991. Feasibility of operational sewer management in Real Time in The City of Zurich, Switzerland, Third European Junior

Scientist course "Applications of Operations REsarch to Real time control of Water Resourse Systems", Formerum, Terschelling, the Netherlands.
James, W. et al., 2008. User's guide to SWMM 5.
Kane, R., 2004. Introduction to Weather Radar Interpretation: Some Useful Insights for the TV Meteorologist.
Kluck, J., Ganzevles, P.P.G., Wijk, M.M.v. and Beenen, A.S., 2005. IBOS Regenwater: the Dutch interactive decision support tool for
sustainable storm water management, 10th International Conference on Urban Drainage, Copenhagen/Denmark.
Kramer, S. and Verworn, H.R., 2008. Improved C-band radar data processing for real time control of urban drainage systems, 11th international conference on urban drainage, Edinburgh, Scotland, UK.
Lee, G. and Zawadzki, I., 2006. Radar calibration by gage, disdrometer,and polarimetry: Theoretical limit caused by the variability of drop size distribution and application to fast scanning operational radar data. Journal of Hydrology 328: 83-97.
Lobbrecht, A.H. and Andel, S.J.V., 2005. Integrated urban and rural water management using modern meteorological data, 10th International Conference on Urban Drainage, Copenhagen, Denmark.
M.Grum, Jørgensen, A.T., Johansen, R.M. and Linde, J.J., 2005. The effect of climate change on urban drainage: An evaluation based on regional climate model simulations, 10th International Conference on Urban Drainage, Copenhagen, Denmark.
M.P.Mittermaier, 2008. Introducing Uncertainty of radar-rainfall estimates to the verification of mesoscale model precipitation forecasts. Natural Hazards and Earth System Sciences, 8: 445-460.
Nelen, F., 1991. Optimize Control of Urban Drainage System, Thirs European junior Scientist Course, Terschelling.
Olofsson, M., 2007. Climate Change and Urban Drainage Future precipitation and hydraulic impact, Luleå University of Technology, Luleå, 74 pp.
Pedersen, L., Jensen, N.E., Rasmussen, M.R. and Nicolajsen, M.G., 2005. Urban run-off volumes dependency on rainfall measurement method - Scaling properties of precipitation within a 2x2 km radar pixel, 10th International Conference on Urban Drainage Copenhagen, Denmark.
Population-Reference-Bureau, 2008. 2008 World Population Data Sheet.
Price, R.K., Mathematical Modelling, LN0251/01/01. UNESCO-IHE for Water Education.
RIONED, 2008. Leidraad Riolering Module C2100 72-73 pp.
Ruggaber, T.P., Talley, J.W. and Montestruque, L.A., 2006. Using Embedded Sensor Networks to Monitor, Control, and Reduce CSO Events: A Pilot Study Environmental Engineering Science.
Schilling, W., 1991. Rainfall data for Urban hydrology: what do we need? Atmospheric Resarch 27: 5-21.
Schu¨tzea, M., Campisanob, A., Colasc, H., Schillingd, W. and Vanrollegheme, P.A., 2004. Real time control of urban wastewater systems—where do we stand today? Journal of Hydrology, 299: 335–348.
Seidler, K.O., 2009. XAMPP.
Steiner, M., Smith, J.A. and Uijlenhoet, R., 2004. A Microphysical Interpretation of Radar Reflectivity–Rain Rate Relationships. Journal of the Atmospheric Sciences, 61(10): 1114-1131.
Toffol, S.D., Engelhard, C. and Rauch, W., 2006. Combined sewer system versus separate system - a comparison of ecological and economical performance indicators, Urban Drainage Modelling and Water Sensitive Urban Design 2006, Melbourne.

V.Gupta, H., Kling, H., Yilmaz, K.K. and Martinz, G.F., 2009. Decomposition of the mean squared error and NSE performance criteria:Implications for Improving hydrological modelling. Journal of Hydrology.

Vieux, B.E., Bedient, B. and Mazroi, E., 2005. Real-time urban runoff simulation using radar rainfall and physics-based distributed modeling for site-specific forecast, 10th International Conference on Urban Drainage, Copenhagen, Denmark.

W.Schilling et al., 1989. Real-Time control of Urban drainage Systems The state-of-the-art.

Woodley, W.L., Olsen, A.R., Herndon, A. and Wiggert, V., 1975. Comparison of Gage and Radar Methods of Convective Rain Measurement. Journal of Applied Meteorology, 14(5): 909-928.

Yuana, J.M., Tilforda, K.A., Jianga, H.Y. and Cluckieb, I.D., 1999. Real-time urban drainage system modelling using weather radar rainfall data Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere 24(8): 915-919.