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The performance of rainfall nowcasts from the Nationale Regenradar for extreme-event rainfall and runoff prediction

A quantitative analysis using FEWS and 3Di

by

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Abstract

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Extreme rainfall can potentially lead to inundation and even damage. Decision-makers can take measures if they have both timely and accurate rainfall forecasts. A short-term rainfall forecast based on the extrapolation of radar images is called nowcast. This thesis studies the performance of nowcasts from the Nationale Regenradar. The historic rainfall is compared with the nowcasted rainfall at several lead times for 3 events: a cold front (13-10-13), a cloudburst (28-07-14) and a thunderstorm (30-05-16); all three events lead to inundation in urban areas. Performance statistics are calculated in FEWS (Flood Early Warning System, a central database containing various modelling tools) and runoff and flooding are modelled in 3Di. The first observation is that the performance of the nowcasts decreases for longer lead times. The maximum lead time for nowcasts found reliable enough is 20(±10) minutes before the extreme rainfall event, depending on the event, region and performance statistic used. The second observation is that the performance also decreases for higher rainfall intensities. The third observation is that the nowcasts underestimate the historic rainfall, varying from 1.3 to 3.3 times, due to errors in the real time radar images. In order to determine the level of nuisance, the nowcasted maximum rainfall is very important. This thesis suggests an improvement of the nowcasts by improving the real time radar images. This can be done by including a correction factor amongst others. The conclusion of this thesis is that there is a potential for using nowcasts as a warning system in urban areas, provided that proper bias-corrections are applied.

Acknowledgements

I would like to thank my supervisors Jeroen de Koning and Marc Bierkens for their helpful comments, reviews of this paper and support. I am also grateful to my colleagues at Nelen & Schuurmans who taught me many new things and provided necessary information and feedback. In particular, I would like to thank Margot Leicher for providing me with the 3Di model, and Jasper van den Heuvel, for helping me with the 3Di modelling. Also many thanks to Lex van Dolderen, and Noud Brasjen from Infoplaza for providing me with the historic and nowcasted rainfall data. Lastly, I would like to thank my family and friends for their support and feedback.

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Abbreviations

A	**A**fter
AWS	**A**utomatisch **W**eer**s**tation
BIAS	bias of an estimator
COR	**C**orrelation
DWD	**D**eutscher **W**etter**d**ienst
FEWS	**F**lood **E**arly **W**arning **S**ystem
HARMONIE	**H**irlam **A**ladin **R**esearch for **M**esoscale **O**perational **N**wp **I**n **E**urope
KMI	**K**oninklijk **M**eteorologisch **I**nstituut
KNMI	**K**oninklijk **N**ederlands **M**eteorologisch **I**nstituut
NC5min	**N**ow**c**asts with **5 mi**nutes lead time
NC30min	**N**ow**c**asts with **30 min**utes lead time
NC1h	**N**ow**c**asts with **1 h**our lead time
NRR	**N**ationale **R**egen**r**adar
NRT	**N**ear **R**eal **T**ime
NWP	**N**umerical **W**eather **M**odel
RT	**R**eal **T**ime
SE	**S**tandard **E**rror of the mean

Chapter 1

Introduction

1.1 Background

Inundation in cities can have severe consequences. Extreme rainfall events (i.e. tens of millimetres in a few hours) can provide so much discharge that sewage systems, basements, roads or other vital parts of a city are filled with water. This will lead not only to inconvenience, but can potentially cause a substantial amount of damage. Examples of this are the water problems in the Netherlands on the 13th of October 2013, 28th of July 2014, and 30th of May 2016 as a result of a passing cold front, a cloudburst and a thunderstorm respectively. The risk of damage can be reduced if adaptation or mitigation measures are taken in advance (Jacks et al., 2010), for example by establishing diversions or by placing sandbags. A good rainfall forecast well ahead of time helps decision-makers to take the appropriate measures. A weather forecast that extrapolates current weather conditions a few hours into the future based on consecutive radar images is called 'nowcast'. For large-scale weather systems, forecasts are based on raw data from rainfall nowcasts and calibrated data from physical-based climate models, which take longer to run. However, small-scale weather systems, such as thunderstorms, develop quickly and calibration might take too much time. For these extreme events, only using nowcasts can be a solution for quick decision making (Jacks et al., 2010). Due to climate change, more extreme rainfall events are expected (Stocker et al., 2013), and therefore the usefulness of nowcasts is likely to increase.

The expected global climate change (Stocker et al., 2013) is translated to climate scenarios for the Netherlands. The four scenarios are: $\mathrm{G_H}$ (Moderate temperature rise, large change in air current pattern), $\mathrm{G_L}$ (Moderate temperature rise, small change in air current pattern), $\mathrm{W_H}$ (High temperature rise, large change in air current pattern) and $\mathrm{W_L}$ (High temperature rise, small change in air current pattern), see figure 1.1.

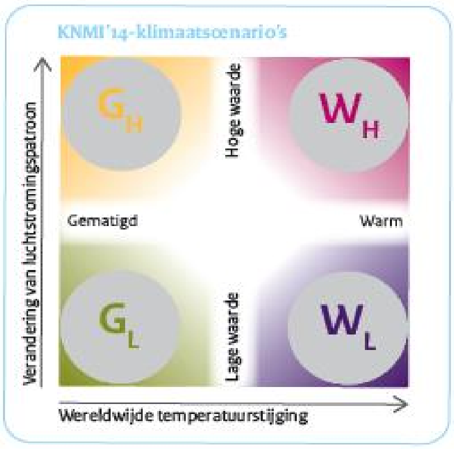

Figure 1.1: Climate Scenarios for the Netherlands (Koninklijk Nederlands Meteorologisch Instituut (KNMI), 2014).

General changes concerning precipitation are the increased intensity of extreme rainfall in summer and heavier storms (Koninklijk Nederlands Meteorologisch Instituut (KNMI), 2014). The $\mathrm{G_H}$ and $\mathrm{G_L}$ scenarios predict one degree of warming for 2050 and the $\mathrm{W_H}$ and $\mathrm{W_L}$ scenarios two degrees of warming. Observations show that the hourly intensity of the most extreme showers increases by about 12% per degree of warming. In 2000, the yearly mean of number of days with minimal 30 millimetres rainfall was 1.2 days. Due to climate change, this number will be doubled in 2100 for the $\mathrm{W_H}$ and $\mathrm{W_L}$ scenarios (Koninklijk Nederlands Meteorologisch Instituut (KNMI), 2014).

1.2 Problem description

The problem description is divided in a societal problem, a scientific problem and a specific problem for the internship organisation.

The *societal problem* is the inconvenience and damage caused by inundation. We cannot prevent extreme rainfall events, but we can take mitigative action and therefore limit the inconvenience and damage.

The *scientific problem* is that there is not enough knowledge about the usefulness of nowcasts for decision-making. Nowcasts, as any other forecast, have limitations. A trade-off has to be made between timely forecasts and scientifically sound forecasts.

The *specific problem for the internship organisation* where the research is performed, Nelen & Schuurmans, partly coincides with the scientific problem, although they are concerned specifically with the type of nowcast they use, namely Nationale Regenradar. Nelen & Schuurmans want to know if their product is good enough to use more extensively or that investments are necessary to improve the quality. The operation of the Nationale Regenradar will be explained in chapter 2: Theory.

1.3 Previous work done

There are several studies researching the limitations and potential of nowcasts. Some studies suggest that combining multiple forecasts, using both physically based models and nowcasts, increases the forecast accuracy (Clemen, 1989; Huang, Isaac, & Sheng, 2012; Golding, 2000; Schuurmans, 2008). However, nowcasts can provide more accuracy for short-term predictions, without needing the high resolution data and time that atmospheric models need (Huang et al., 2012). Although the limitations of nowcasts are widely acknowledged (see chapter 2), there are few case studies comparing the forecasted rainfall by nowcasts and measured rainfall. Van Steijn and Schuurmans (2014) researched the difference between the measured rainfall in rain gauges of the KNMI and of the Nationale Regenradar data, also on the 28th of July 2014, yet their focus was on the difference between the Nationale Regenradar data and rain gauge data, not on nowcasts. Nowcast data of the Nationale Regenradar are currently not saved in the Netherlands; only the historic data from 2010 onwards are saved. Therefore, a study comparing the forecasted rainfall by the Nationale Regenradar and measured rainfall is unique. Moreover, the performance of nowcasts in runoff projections has not been studied yet. The nowcast data needed for the case study of the 13th of October 2013, 28th of July 2014 and the 30th of May 2016 will be retrieved specially for this project (see chapter 3: Materials and methods - Data collection).

There is need for research on changes in regional extremes in such a way that stakeholders have enough knowledge and certainty to take mitigating action (Pidgeon & Fischhoff, 2011; Leskens, 2015). The uncertainties in the outcome should not be too substantial to inform decision-makers. The more accurate the forecast, and the longer the lead time, the better water managers can anticipate on extreme rainfall events (Projectgroep Nationale Regenradar, 2013).

1.4 Aim

The aim of this thesis is to determine if nowcasts during extreme rainfall events are both reliable and timely enough to be used for quick decision making. In short, this thesis attempts to find out if the forecasted rainfall using nowcasts is the same as the actual measured values. Moreover, this thesis attempts to investigate to what extent predicted runoff differs if nowcasts are used and if this results in different water nuisance.

1.5 Research questions

The main research question is:

> *"How accurate are rainfall nowcasts compared to historical rainfall estimates and how do hydrodynamic runoff forecasts from nowcasted rainfall differ from historical runoff simulations?"*

Related to this main research question the following additional questions will be answered:

1. Are nowcasts of the Nationale Regenradar good enough in their current form or do they need improvement?

2. What effect has the type of precipitation on the performance of nowcasts?

1.6 Outline

This thesis is divided in six chapters, followed by the bibliography and eight appendices. Chapter 2 explains the relevant theory. Chapter 3 describes how the research is carried out. The results are presented in chapter 4. The results are placed in a wider context and recommendations are given for further research in chapter 5: Discussion. In chapter 6: Conclusion, the research questions will be answered.

Chapter 2

Theory

In this chapter, the relevant theory consulted for this thesis will be set forth. Firstly, nowcasts and their limitations will be discussed. Secondly, different types of precipitation are discussed. Lastly, the operation of the Nationale Regenradar will be described.

2.1 Nowcasts

As explained in chapter 1, nowcasting is a useful tool for providing short-term rainfall forecasts. Nowcasting is a long-established technique in which the current motion of meteorological features is extrapolated for several hours into the future based on current and recent weather observations (Sene, 2013), based on a variety of sources (Huang et al., 2012). For most forecasts, this nowcasting is combined with calibrated data from climate models including physical laws. Nowcasting does not include physical laws (Schuurmans, 2008). The assumption used with nowcasting is that ”the rate of change is constant or involving various empirical and rule-based constructs” (Huang et al., 2012). Therefore, nowcasting proves to be insufficient for a lead time for generally more than six hours (Huang et al., 2012), and even rapidly loses accuracy after three hours (Austin & Bellon, 1974; Browning & Collier, 1989; Lin et al., 2005). The lead time is the time between the moment the forecast is available and the time for which the forecast is given. The lead time accuracy becomes even shorter for extreme rainfall events that develop in a short time span. Another limitation of nowcasting is that it is highly location specific (Huang et al., 2012). To extend the lead time of an accurate forecast, a combination with numerical weather prediction (NWP) models is commonly used (Liguori & Rico-Ramirez, 2012). An example of a NWP is HARMONIE, a model used in the Netherlands with a resolution of 2.5x2.5km.

However, NWP models perform less than nowcasts at the short-term nowcast range (0-6 hours), because of "spinup effects, imperfect assimilation algorithms, time delays with assimilation analysis, and models having too coarse a spatial and temporal resolution" (Bock & Nuret, 2009; Dee, 2005; Polavarapu et al., 2005) as cited in (Huang et al., 2012). Because of the short lead time, nowcasts can only be used for quick-decision making. This thesis attempts to find out if this time is enough for decision-makers and if nowcasts are good enough to forecast the rainfall. This thesis investigates for how many minutes or hours nowcasting proves to be sufficient. *The first hypothesis of this thesis is that nowcasts are reliable and timely enough for decision-makers to use to take action.*

2.2 Precipitation types

The performance of the rainfall forecast is expected to depend on the type of rainfall. We define three types of rainfall based on movement: convective (vertical rise of air due to convection), stratiform (diagonal rise of large air masses due to larger-scale atmospheric dynamics) and orographic (diagonal rise of large air masses due to the encounter of a rising slope, e.g. a mountain). Stratiform and orographic rainfall are characterised by drizzling rain that can last for several hours. Convective rain is characterized by short, intense showers. We also define warm (Fig. 2.1) and cold fronts (Fig. 2.2). A front is the division between two air masses.

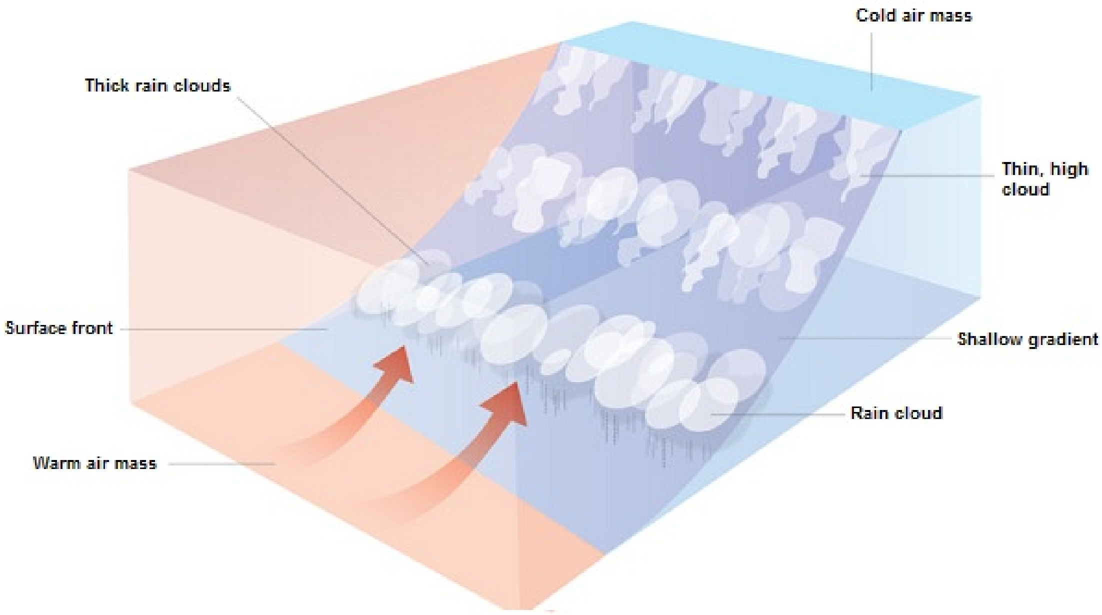

Figure 2.1: A warm front (Met Office, n.d.).

A warm front is a warm air mass that replaces a cold air mass. A cold front is the opposite, a cold air mass that replaces a warm air mass (Met Office, n.d.). Generally, warm fronts result in little, drizzling rain or no rain.

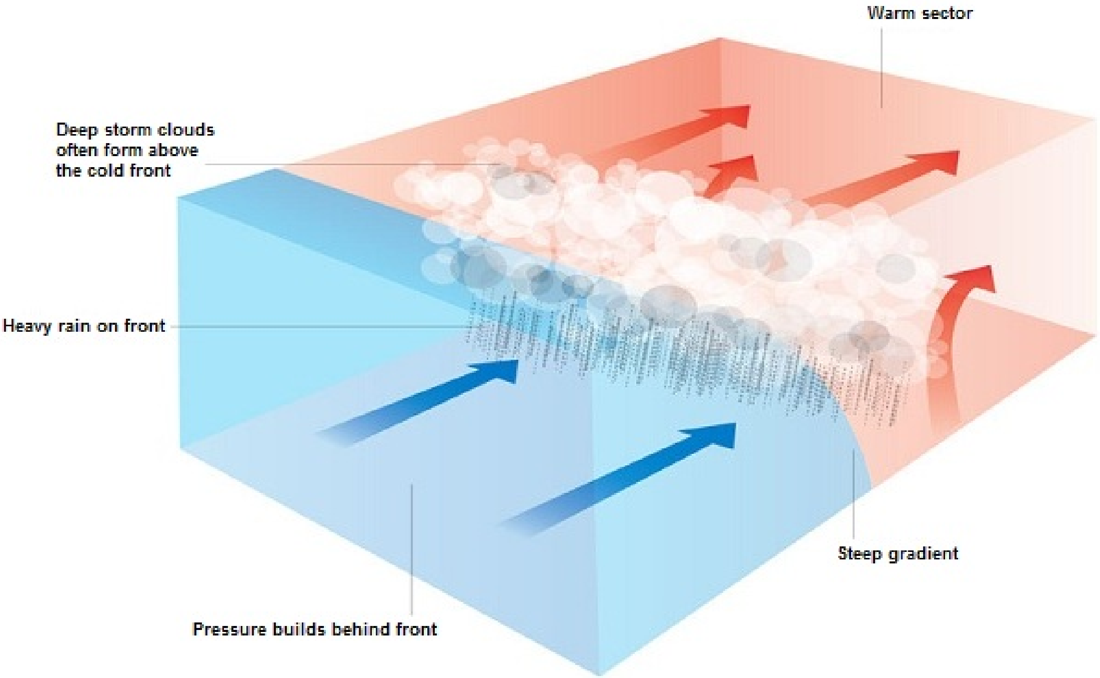

FIGURE 2.2: A cold front (Met Office, n.d.).

Ahead of a cold front, precipitation may develop in a narrow band. Because of the steep slope, this can result in intense showers and thunderstorms (University of Illinois, n.d.). Due to this narrow band, the rainfall can be more easily extrapolated than a broad area of rainfall. *The second hypothesis of this thesis is therefore that rainfall caused by cold fronts is easier to forecast than other precipitation types, in this case study, easier than convective rainfall.* However, not only the amount of rainfall is accountable for water problems, but also the layout, i.e. the subsurface, amount of vegetation and sewage system operation (Rainproof, n.d.).

2.3 Nationale Regenradar

The Nationale Regenradar (NRR) delivers historic, real time and nowcast images for the whole of the Netherlands. NRR has input data from radar images and ground stations. The real time and nowcast images are solely based on the radar images. Therefore, it is important to know how the radar images are realised.

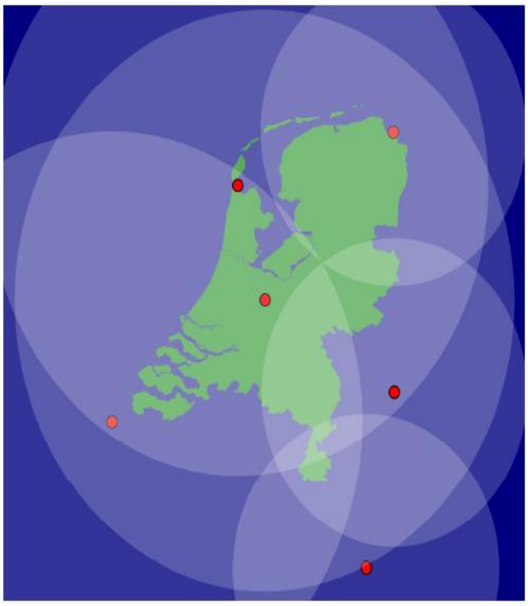

FIGURE 2.3: Six measuring stations (Projectgroep Nationale Regenradar, 2013).

There are six different radar stations (Fig. 2.3): two in the Netherlands, one in Belgium and three in Germany. By combining these radar data, the whole area of the Netherlands is covered. In the Netherlands, the radar images are delivered by the KNMI, obtained from radars in Den Helder and De Bilt. The radar antennas cover a radius of 150 kilometres at a varying elevation, with a resolution of 1x1km (Koninklijk Nederlands Meteorologisch Instituut (KNMI), n.d.-a). The radar images in Germany: Emden, Essen and Neuheilenbach are delivered by the Deutscher Wetterdienst (DWD) and in Belgium by the KMI in Jabbeke. Because these radars obtain their data differently than the KNMI ones, a composite has to be made of the six images. The radar images are available after each five minutes.

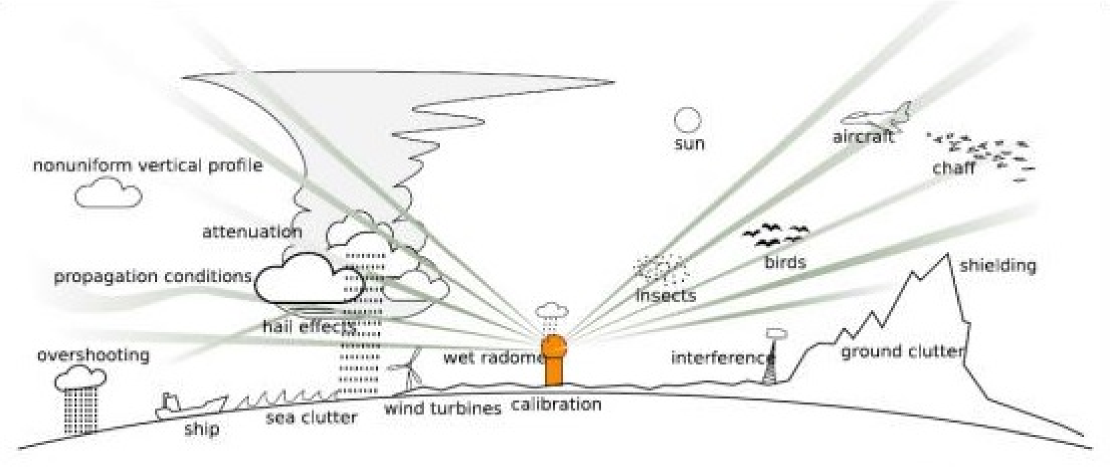

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FIGURE 2.4: Schematic overview of possible distortions to the radar (Markus Peura, Finnish Meteorological Institute).

A radar does not measure rainfall, but the reflectance of electromagnetic waves. For most weather services, a C-band radar with wavelength 3.75-7.5 cm and a frequency of 4-8 GHz is used. However, measurement errors can occur due to distortions of the reflection signals by for example aviation paths and wind mills. Moreover, it is not possible to look through a dense cloud. The radius of the range of radar images is also limited because of the curvature of the earth surface (Fig. 2.4). The relationship between the reflectance (Z) and rainfall intensity (R) is called the Z-R relationship (Equation 2.1)(Projectgroep Nationale Regenradar, 2013). This relationship is dependent on the type of rainfall, although the equation is static. In reality, the factor 200 varies between 150 and 250.

$$Z = 200R^{1.6} \tag{2.1}$$

Because of these limitations, it is important to correct the radar data with measured rainfall at ground stations. Every 10 minutes data from 35 automatic rainfall stations (AWS) are available, used for calibration of the 1-hour radar images. Every 24 hours rainfall data are available based on a volunteer network of around 330 rainfall gauges, used for calibration of the 24-hour radar images (Schuurmans & De Koning, 2011). Radar images give the best insight in the spatial variation of rainfall while rain gauges give more insight in the quantity, but only for their direct environment (Projectgroep Nationale Regenradar, 2013). It is important to keep in mind that without calibration, the errors in the radar images are extrapolated in the nowcasts.

Chapter 3

Materials and methods

In this chapter is described how the research is carried out. It contains which steps have been taken and why those steps had to be done. Firstly, the general approach will be discussed (3.1). Secondly, the data collection will be explained (3.2). Thirdly, the three historic rainfall events focused on in this thesis will be described (3.3). Hereafter, the locations of the research areas will be presented (3.4). Subsequently, the data analysis and the steps taken are elucidated (3.5). Lastly, there will be explained how the applied methods would answer the research questions (3.6).

3.1 General approach

A quantitative analysis of a forecasted rainfall event will be made using both nowcasts and historic (calibrated) data, collected from the Nationale Regenradar, as input and by comparing their effect on predicted runoff. The analysis will be performed for three particular historic events: 13 October 2013, 28 July 2014 and 30 May 2016. These particular events have been selected because they will show the potential of nowcasts in extreme rainfall events. Moreover, the type of rainfall differs. Firstly, the difference in the forecasted and measured rainfall will be compared, by using the program FEWS: Flood Early Warning System and applying basic statistics. Secondly, the computation of runoff by the forecasts will be done using the program 3Di, only for one specific region with input data from 28 July 2014.

3.2 Data collection

Firstly, the theory behind nowcasts, extreme rainfall events and climate change is reviewed through a literature search. Insight into the operation of the Nationale Regenradar is obtained from the website www.nationaleregenradar.nl, personal connections at Nelen & Schuurmans and from an interview at Infoplaza (see appendix 1). The information on the rainfall events are primarily obtained from news articles and interviews with water managers and concerned municipalities. The historic rainfall data are obtained from the Nationale Regenradar (NRR). Specific rainfall at the date, time and location is available. FEWS presents the NRR data in maps and as graphs and shows the basic statistics (e.g. mean and standard deviations) and provides the possibility for statistical analyses. Deltares (n.d.-a) gives the following description of FEWS:

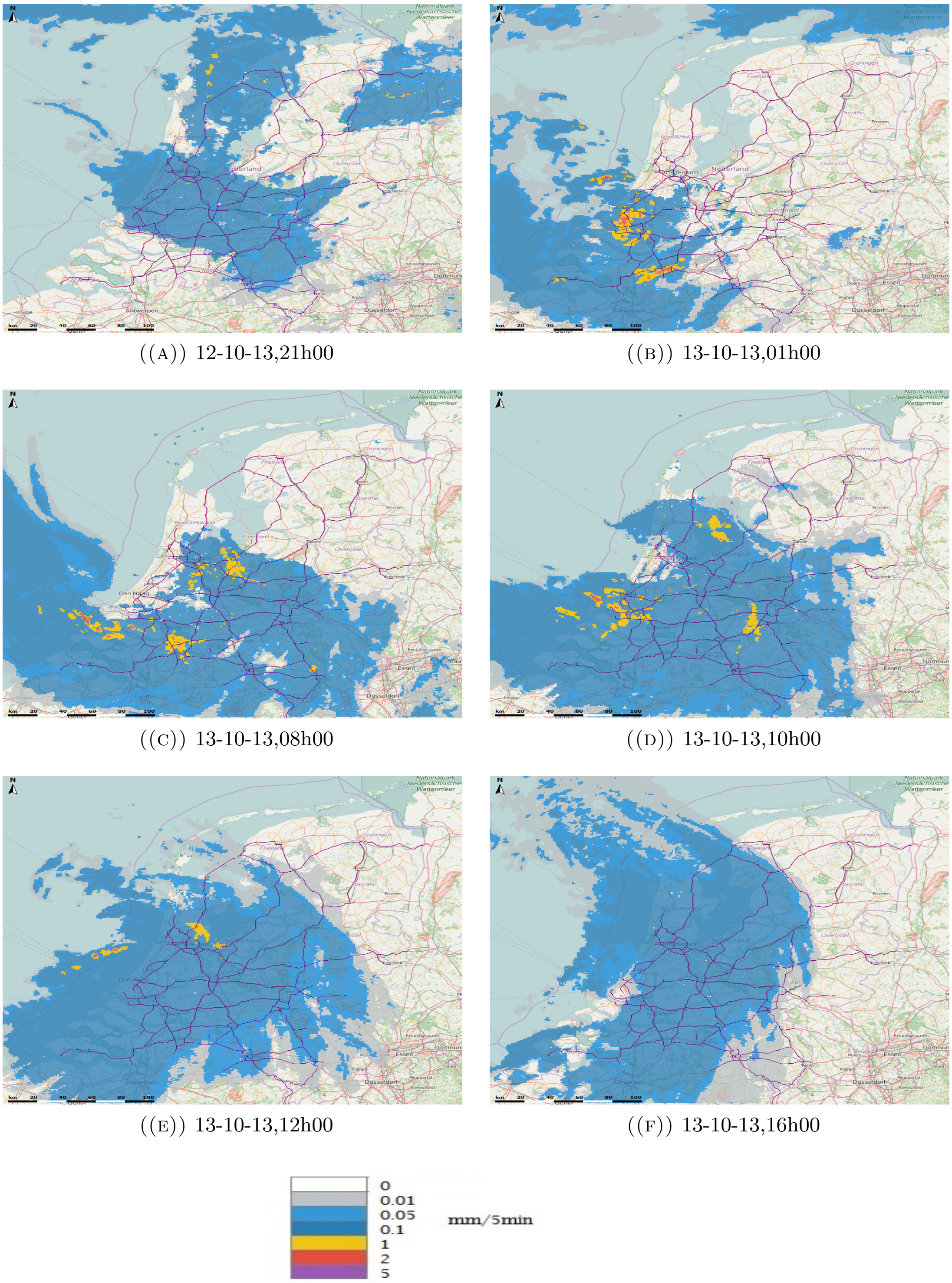
> *Delft-FEWS is an open environment for the application of various modelling tools build-up around a central database. A set of standard tools related to data handling is available. This includes modules for importing and exporting data, validation of data, interpolation of data (both filling gaps in time, as well as in space) and transformation of series (aggregation, disaggregation, and transformation)* (p.2).

Rainfall datasets, delivered by the NRR, are available into FEWS as Real Time (RT) (not calibrated), Near Real Rime (NRT) (partially calibrated) and After (A) (finally calibrated). The RT data are available every 5 minutes, NRT every hour and A every 48 hours. Moreover, the data are available for different time frames: 5 minutes, 1 hour and 24 hours. The A dataset is used in this thesis as historic dataset. The time frame of 5 minutes of the A data set is used in order to compare it with the nowcast, which also has a time frame of 5 minutes.

The nowcast data are delivered by Infoplaza and are then imported in FEWS. The nowcast data are imported for a lead time from 5 minutes to 2 hours. A lead time of 5 minutes means that there are five minutes between the availability of a forecast and the time for which the forecast is made. As explained in chapter 1, the accuracy of the forecast decreases with an increasing lead time, and the nowcasts prove to be insufficient for a lead time for more than 1 hour in this case study, after a visual inspection. The nowcasts with a 5 minute lead time are expected to resemble the historic rainfall. However, a warning system should at least be in place for 30 minutes in advance of the rainfall in order to take timely measures. Therefore, the nowcast data from every five minutes from 5 minutes to 1 hour are analysed, and the graps and maps of 5 and 30 minutes and 1 hour are compared.

3.3 Rainfall events

3.3.1 13 October 2013



((A)) 12-10-13,21h00

((B)) 13-10-13,01h00

((C)) 13-10-13,08h00

((D)) 13-10-13,10h00

((E)) 13-10-13,12h00

((F)) 13-10-13,16h00

FIGURE 3.1: The development and the course of the storm on 12 to 13 October 2013. Data are imported from NRR and shown in FEWS.

On the night of the 12th to the 13th of October 2013, a cold front was passing over the Netherlands (Fig. 3.1), resulting in rainfall runoff in many areas in the Netherlands. In advance, The KNMI brought out a warning signal for the province of Zeeland, Zuid-Holland, Utrecht and Noord-Holland for the expected extreme rainfall. However, the forecast by HARMONIE was completely off (Fig. 3.2). The forecast underestimated the measured rainfall, at some places exceeding 100 millimetres that day. Moreover, the centre of the front was predicted to be over sea, which turned out to be over land.

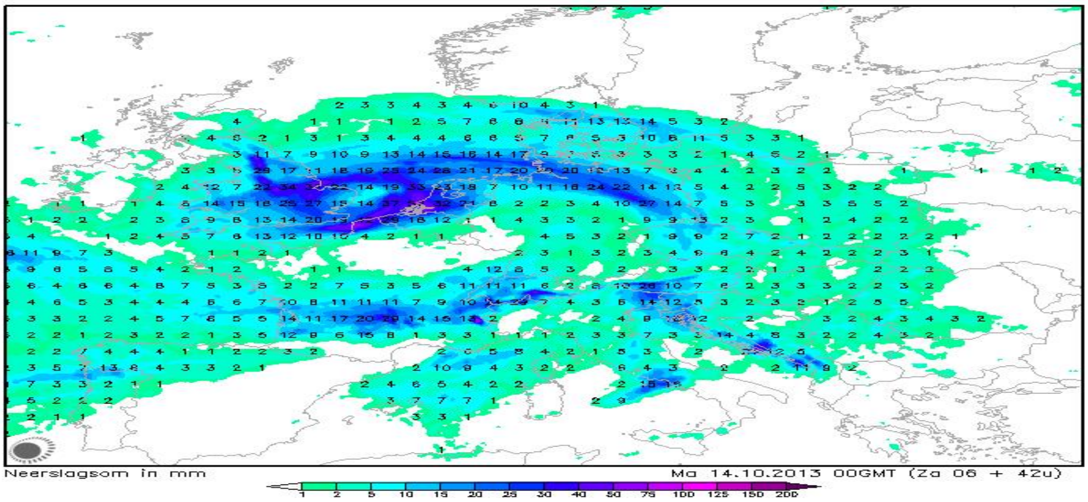
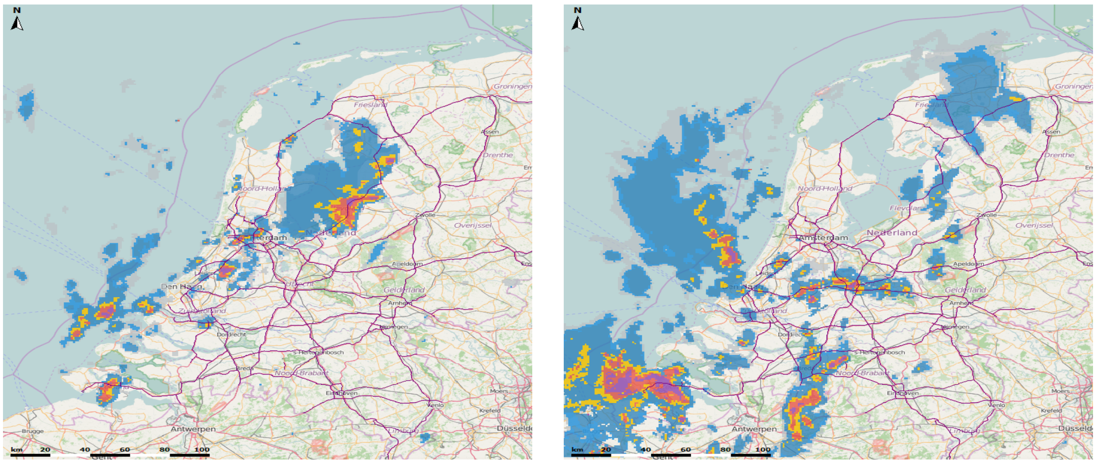


Figure 3.2: Total rainfall on the 13th of October, expected by the HARMONIE model 42 hours in advance.

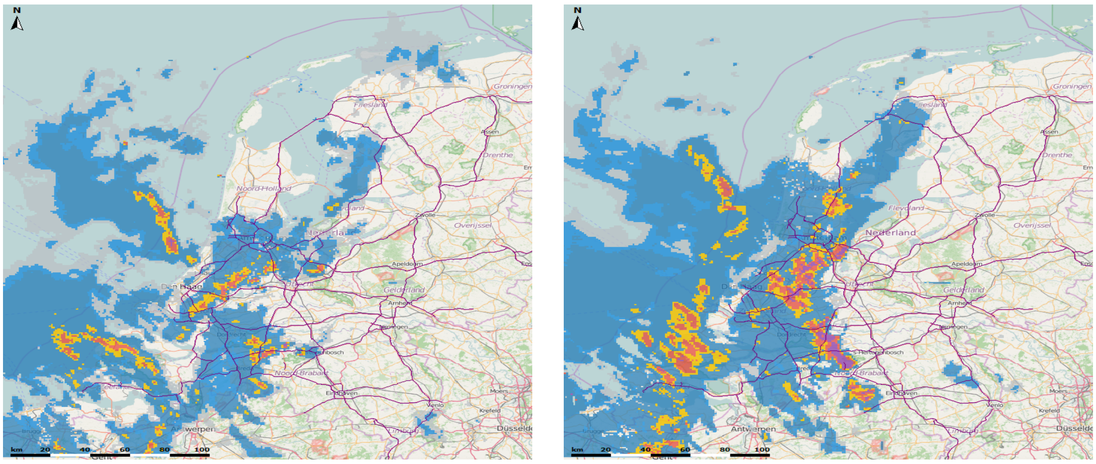
3.3.2 28 July 2014

On Monday the 28th of July 2014 there was a cloudburst in the Netherlands, also resulting in rainfall runoff in many areas and it was one of the wettest days ever recorded (Fig. 3.4). In Amsterdam between 50 and 80 millimetres of rain fell during one event and in Alphen aan de Rijn 181 millimetres in 24 hours, resulting in considerable damage in both cities (Fig. 3.3). In some locations rainfall intensities were as high as 40 millimetres per hour, and even 12 millimetres in 5 minutes. These are very extreme rainfall totals (Rainproof, n.d.). The cloudburst was a result of convective rainfall.

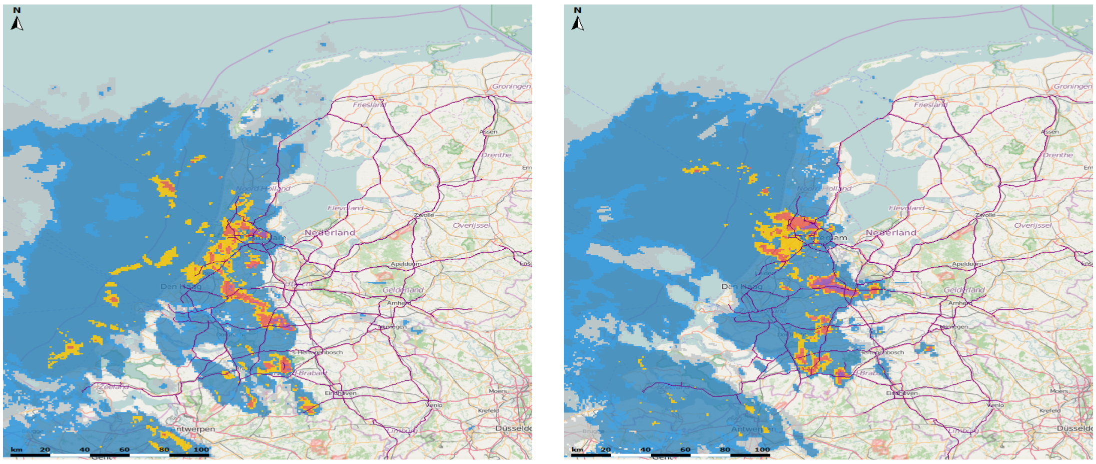
Figure 3.3: Water runoff on 28 July 2014 in Amsterdam (left) and Alphen aan de Rijn (right) (Photos made by Robin Kok and Martijn van der Zande, respectively).



((A)) 28-10-14,3h30 ((B)) 28-10-14,7h00



((C)) 28-10-14,8h00 ((D)) 28-10-14,9h00



((E)) 28-10-14,10h00 ((F)) 28-10-14,11h00

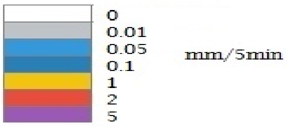
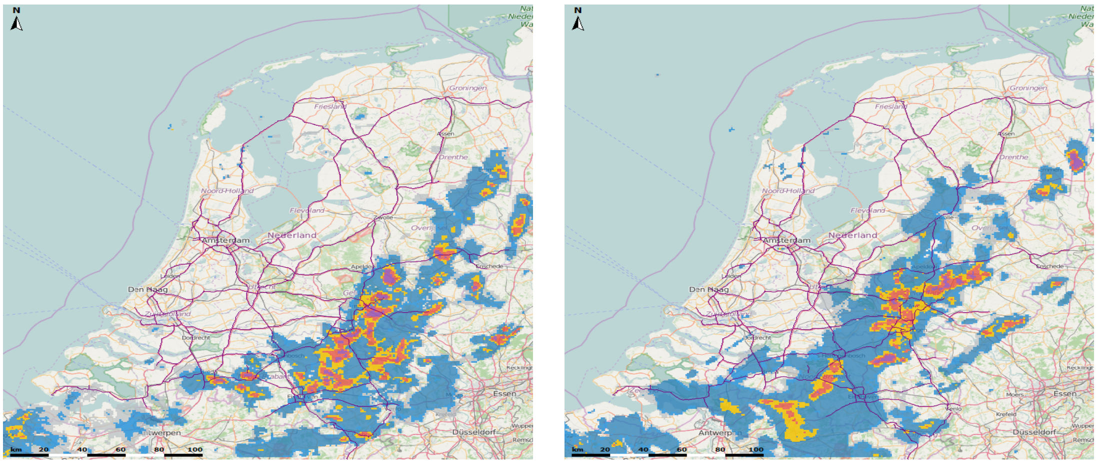


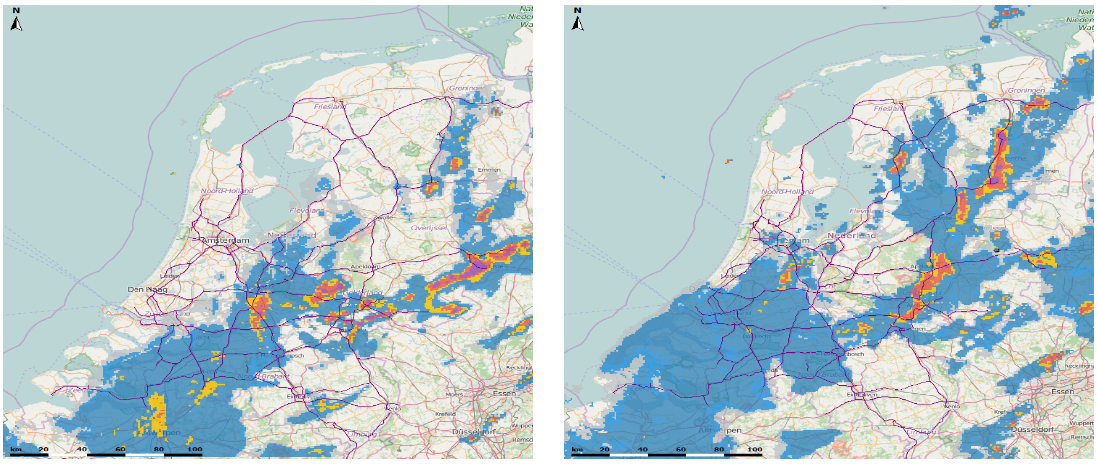
FIGURE 3.4: The development and the course of the cloudburst on 28 July 2014. The rainfall data are imported from NRR and shown in FEWS.

3.3.3 30 May 2016

On Monday the 30th of May 2016 major thunderstorms were passing over the south-eastern part of the Netherlands, resulting in rainfall runoff in many areas (Fig. 3.5). In some places rainfall totals were between 60 and 80 millimetres (Fig. 3.6). Amongst other cities, Apeldoorn and Arnhem (Fig. 3.7) experienced floodings. The thunderstorms were a result of unstable air, which in turn was a result of a low pressure area that contained warm and moist air. The type of rainfall is also convective rainfall (Koninklijk Nederlands Meteorologisch Instituut (KNMI), n.d.-b).



((A)) 30-05-2016,17h00 ((B)) 30-05-2016,18h00



((C)) 30-05-2016,19h00 ((D)) 30-05-2016,20h00

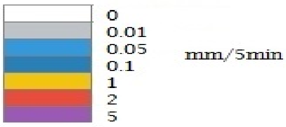


FIGURE 3.5: The development and the course of the thunderstorms on 30 May 2016. The rainfall data are imported from NRR and shown in FEWS.

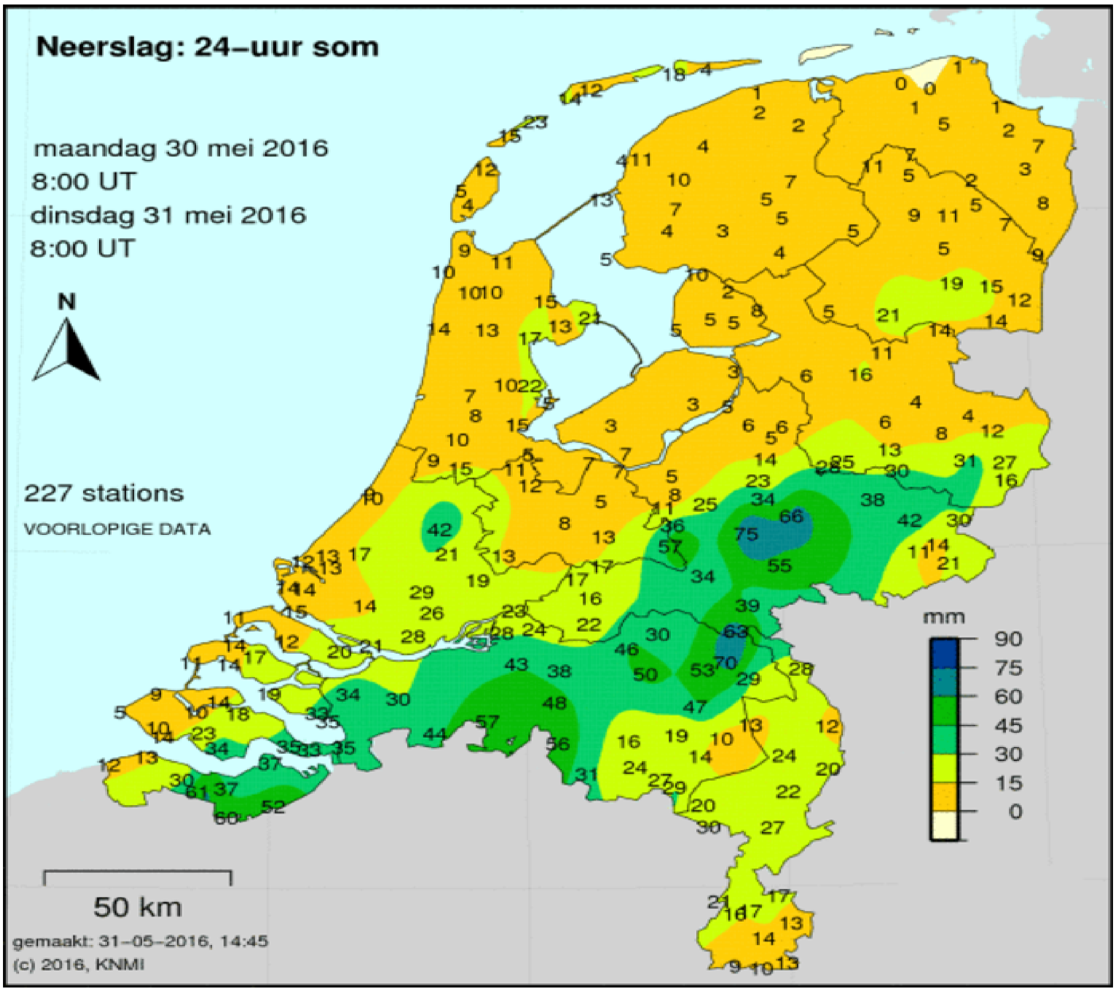


FIGURE 3.6: Total rainfall from 30 May 2016 8h00 to 31 May 2016 8h00 (Koninklijk Nederlands Meteorologisch Instituut (KNMI), n.d.-b).

FIGURE 3.7: Water runoff on 30 May 2016 in Arnhem (Photo by Omroep Gelderland).

3.4 Locations

At first, the statistical analysis of the performance of nowcast in FEWS is done for the total area of the Netherlands, as the NRR operates for the whole of the Netherlands, and the rainfall is passing along a large part of the Netherlands. However, as extreme rainfall events are very location specific, it is more interesting to focus on some extremes. In FEWS, the statistics are calculated per pixel of 1x1km, but it is also possible to import polygons of e.g. municipalities and countries. These polygons will then show the mean value over the pixels that are part of the polygon. As the showers have a surface area of approximately 5x5km and the resolution of the NRR is only 1x1km, the areas over which the statistics are calculated should be at least 3x3km, to avoid coincidence. For example, the shower can be entirely in a cell and have a perfect score, or entirely out the cell and have a very low score, while the shower could be in the next cell and have equal damage.

After the rainfall analysis, the following three regions are chosen per event. For 2013, the cold front had few extremes, but the most accumulation is found in Maassluis, Amsterdam and Purmerend. The municipalities of Amsterdam, Alphen aan de Rijn and Urk are chosen for 2014. Amsterdam and Alphen aan de Rijn experienced a quickly developing shower and it practically maintained at the same position. The shower in Urk seemed to develop more gradually and earlier in the night and moved from the south west to the north east. Admittedly, the region used for Urk is 1.5x1.5km, and thus does not fit the minimum 3x3 condition. For 2016, the regions of Arnhem, Zutphen and Enschede are chosen. The regions used are presented in a map in appendix 2, with also their maximum hourly rainfall sum. The specific case study in 3Di depends firstly on available models. Secondly, the municipality should have been affected by the extreme rainfall event. Therefore, a region in Amsterdam is chosen that is known to experience floods on a regular basis. This region is also presented in appendix 2.

3.5 Data analysis

The following sections describe the analyses of the performance of the rainfall nowcasts, the 3Di modelling and the performance of the 3Di flood forecasts.

3.5.1 Step 1: Data analysis of the rainfall in FEWS, performance of the nowcasts

In step 1 of the research, the rainfall is analysed with FEWS and the performance of the nowcasts is determined (see Fig. 3.8). In step 1a, the analysis is done for 13 October 2013, in step 1b for 28 July 2014 and in step 1c for 30 May 2016. In step 1d, the results are compared. In step 1e, the influence of the rainfall intensity on the performance is evaluated. For step 1a, 1b and 1c, the graphs and maps of the historic, "observed" (dataset A), rainfall are compared with the maps and graphs of the nowcasted rainfall at several lead times (5 and 30 minutes and 1 hour). The time series are compared visually, but also by using statistical functions. Note that what is called "observed" rainfall is in fact the rain-gauge corrected and calibrated radar product from the NRR. This is the best possible estimate of the actual rainfall and is therefore used as a reference.

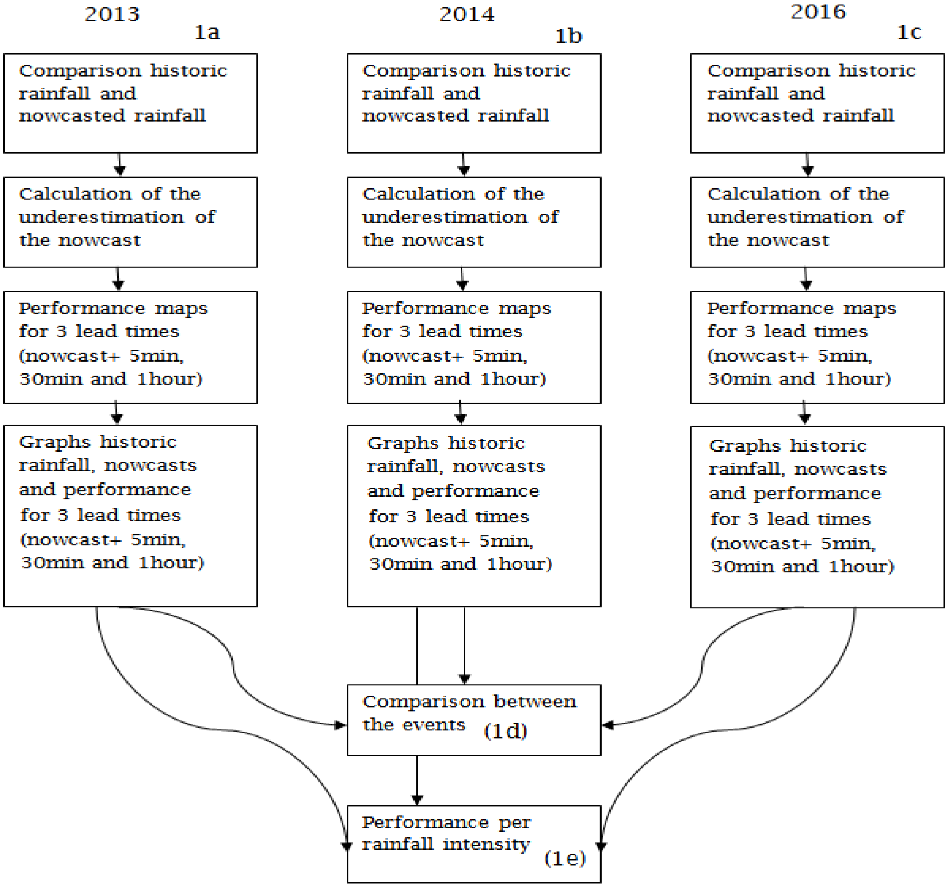


FIGURE 3.8: This flowchart is a schematisation of the steps taken in step 1.

Underestimation

After a visual inspection, it appears that the RT radar images are consequently underestimating the historic rainfall. This has an effect on the performance of the nowcasts. The underestimation of the nowcasts is determined as follows: the sum, mean and max of the historic rainfall and of the nowcasts with a lead time of 5 minutes are compared. The sum, mean and max of the historic rainfall is divided by the sum, mean and max of the nowcasts respectively. This is done for the Netherlands as a whole and separately for the focus regions. For the nowcasts a lead time of 5 minutes is chosen as they are expected to almost perfectly resemble the RT, which are not available in this study.

Performance

In order to determine the performance of nowcasts, the bias of an estimator (BIAS), standard-error-of-the-mean (SE) and correlation (COR) are calculated for each lead time per region. By doing so, maps and graphs can be made showing the BIAS, SE and COR over the region per lead time. For all three statistical analyses, the average over the last hour is calculated. The maps and graphs are inspected and described. By applying the following formula (Equation 3.1), the difference between the expected value and the true value of the parameter (i.e. BIAS), in this case the amount of rainfall, is calculated. The BIAS gives insight in systematic errors. For BIAS, the closer to 0 it is, the better the performance is.

$$BIAS =^1 /_n \sum_{i=1}^{n} (\hat{x}_i - x_i) \tag{3.1}$$

Where '$\hat{x}_i$' is the estimated value (i.e. nowcasted rainfall), 'x_i' is the reference value (i.e. historic rainfall), and 'n' is the number of data points in the timeframe considered (Deltares, n.d.-b).

The SE, calculated by applying the following formula (Equation 3.2), gives insight in random errors. For SE, the closer to 0 it is, the better the performance is. The BIAS squared is subtracted from the RMSE (Equation 3.3) squared, over which the square root is taken.

$$SE = \sqrt{(BIAS^2 - RMSE^2)} \tag{3.2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\hat{x}_i - x_i)^2}{n}} \tag{3.3}$$

In figure 3.9 three pictures are depicted. In the upper left picture a scenario is shown with a high to average SE and minimal BIAS. It means that the calculated value is not concentrated around the measured, true value, but also not above or below the measured value on average. In the upper right picture a scenario is shown with a high to average BIAS and minimal SE. This means that the values are concentrated at one value, but that that value is, in this case, too low. In the lowest figure a scenario is depicted that contains both. It is expected that the nowcasts also contain both BIAS and SE.

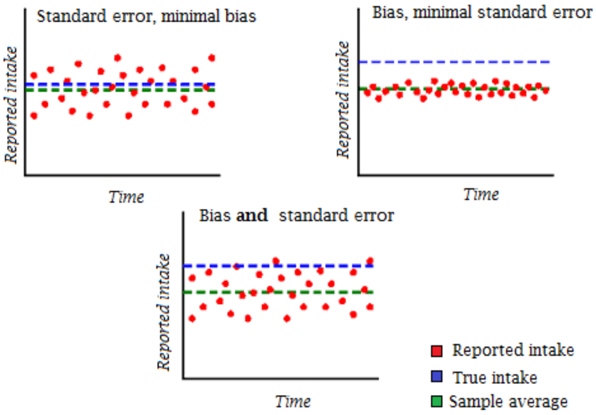


FIGURE 3.9: Examples of bias and/or error (adapted from Centers for Disease Control and Prevention).

For the correlation several scripts are available. The script of the correlation, as well as the other scripts are available in appendix 3. The correlation provides insight in the timing of time series. A good correlation, approaching 1, means that the graphs follow the same curve and that peaks are at the same time. There can also be a negative correlation. If the correlation approaches -1, the peaks are opposite, meaning: if the historic rainfall has a high rainfall peak, the nowcasts predicted it to be dry and vice versa. This is, of course, for rainfall predictions an undesirable situation.

Rainfall intensity

In step 1e, the performance of the nowcasts is determined per rainfall intensity. In appendix 2, the rainfall sums per hour for the chosen regions are available. The results per intensity are ordered in appendix 5.

3.5.2 Step 2: Maximum lead time

Having calculated the BIAS, SE and COR, the question arises what their value implies for the ability to use nowcasts of different lead times previous to or during rainfall events. In other words, until what value of BIAS, SE and COR is the nowcast considered good enough? In order to give an answer to this question, the BIAS, SE and COR of all lead times are compared with the values of the nowcast with 5 minutes lead time (from now on: NC5min). The pattern of the NC5min and historic rainfall coincide well, visually and quantitatively. Therefore, the NC5min is assumed to be the actual rainfall. Moreover, by doing so, the underestimation has no influence on the maximum lead time.

The maximum lead time at which the nowcast performs well is defined as follows (see Fig. 3.10): for the BIAS, SE and COR, the value of the NC5min is taken plus or minus the standard deviation, depending on the statistic. A perfect BIAS is 0. In this study the BIAS is mostly negative because of the underestimation, and therefore the worst BIAS is the minimum value. The minimum BIAS value of the NC5min (averaged over the region) minus the standard deviation is taken. All nowcasts with lead times resulting in a minimum BIAS under this value are considered to be insufficient. A perfect SE is also 0, and is always positive by definition. The maximum SE value plus the standard deviation of the NC5min is taken, as that is the maximum acceptable SE. For COR the value 1 is perfect. For correlation, the mean value gives the most insight. The mean COR minus the standard deviation is taken, which is the minimum value considered sufficient. The computation is then:

BIAS → minimum BIAS should be larger than
minimum BIAS (for lead time considered) - standard deviation COR NC5min
SE → maximum SE should be smaller than
maximum SE (for lead time considered) + standard deviation SE NC5min
COR → mean COR should be larger than
mean COR (for lead time considered) - standard deviation COR NC5min

This is done for all regions and all lead times from 5 minutes to 1 hour, every 5 minutes.

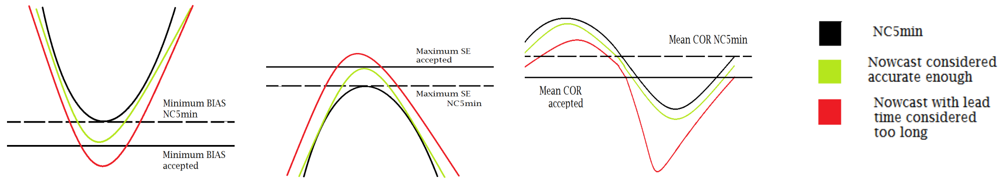


FIGURE 3.10: This figure shows a schematic overview of the determination of the maximum lead time defined by BIAS (left), SE (middle) and COR (right).

3.5.3 Step 3: Modelling with 3Di

The third step is to model the rainfall events and resulting water damage, with both input from nowcasted data and historical data. The modelling program used is 3Di (www.3di.nu). 3Di simulates water flow, taking into account the subsurface with the possibility to include human intervention. This is done for a specific area in Amsterdam, as shown in appendix 2. The model includes a rainwater sewage system with outlets. The model is a combined 1D and 2D model: the sewage system is 1D (i.e. it can only flow in one direction) and the surface is 2D (i.e. water can flow in all x,y directions). Rainfall is placed 2D over the area. It does not vary spatially, but the amount does vary through time, defined by the inputs. The runoff is dependent on the location of the rainfall and the route it covers. The water can travel to the sewage system, it can percolate in the subsurface, it can remain on the roofs or it can inundate on the street. Inundation takes place if the sewage system overflows, even after the use of outlets, or if the water can not travel through the sewage system or percolate.

The only variable that is changed before running the simulations is the rainfall data. Seven simulations are run. One with input data from the historical rainfall, averaged over the region Amsterdam from 28 July 2014 07h30-15h30. Three with the nowcasted data from the same time with lead time 5 minutes, 30 minutes and 1 hour (from now on NC5min, NC30min and NC1h, respectively). Also three simulations with the nowcasted data for the three lead times times two (from now on 2xNC5min, 2xNC30min and 2xNC1h). 2.0x is the correction factor used because of the underestimation. The results are visualised in QGIS. Pictures are presented of the maximum inundation depth for the historic rainfall and the (un)corrected nowcast. Moreover, pictures are made of the duration of water on street. The duration of water on street is defined as follows: it is the sum of every timestep the water is above surface level during the simulation.

After the simulations, the potential water damage due to the rainfall becomes visible. Moreover, the effect of different input data on the result becomes visible. A different result is that the water reaches other places and earlier than expected or that the inundation height or the duration of inundation is different.

The modelling is partly fictional: the water damage simulated with the historical rainfall is not exactly the same as that actually occurred on 28 July 2014. The modelling is solely used to answer the question: "What would happen if this amount of rain would fall and what is the difference between the historic and nowcasted rainfall as input?"

3.5.4 Step 4: Statistics of effect nowcasts on projected runoff

The fourth and last step of the research is to apply a statistical analysis on the differences between forecasted 3Di runoff using the rainfall nowcasts and predictions obtained with the historical rainfall. For example: "the water level becomes 10% lower if nowcast data are used as input". The area with the highest water level as simulated with the historical rainfall data is used. The maximum inundation depth and the duration are presented at specific locations as points. Each point has a minimum, maximum and average value. The average values of the mean and the maximum value of the points are compared for the historic, NC5min, NC30min, NC1h, 2xNC5min, 2xNC30min and 2xNC1h as these give the most insight into potential water damage. According to van Luijtelaar (2006), water on street with a duration of 15-30 minutes is called a small nuisance. A duration of 30-120 minutes, or 'large quantities' is called a large nuisance. No definition on the amount is found. This thesis uses the following definition of a large nuisance: longer than 30 minutes water on street and/or a maximum inundation height higher than 15 centimetres.

3.6 Answering the research questions

The first, main research question is to what extent the output of the rainfall and runoff differs. The difference in rainfall output is answered by using statistics in step 1. The difference in runoff is answered by the modelling (step 3) and statistics (step 4). The answer to this question can be a difference in amount of runoff measured, but also in duration.

The first sub question is if nowcasts need improvements and if there is a potential for nowcasts to be used as some kind of warning system. This is dependent on the modelled and calculated difference and on the maximum lead time. If the difference is relevant, i.e. the sewage flows over or the maximum duration of 30 minutes is reached, the nowcasts from the NRR need to be improved in order to use more extensively. If the difference is irrelevant or the lead time is too short, then there is no reason to improve the nowcasts from NRR. The underestimation should also be included.

The second sub question is if there is a difference of the performance of nowcasts during different types of precipitation. In this thesis a convective rainfall event and the passing of a cold front are compared, which gives an answer to the research question what the effect of type of precipitation is on the performance of nowcasts. Moreover, the influence of the rainfall intensity on the performance is determined.

Chapter 4

Results

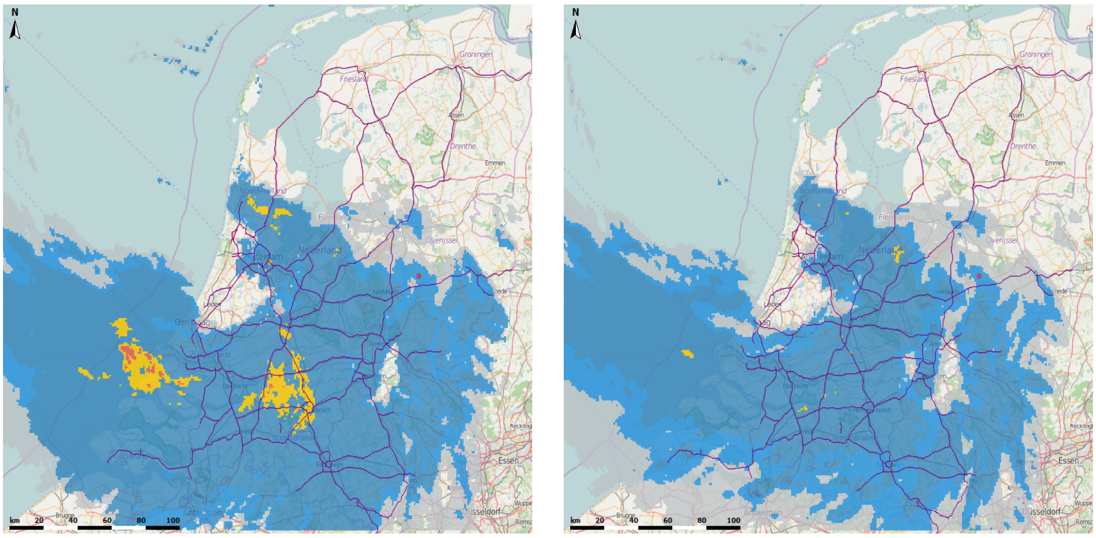
In this chapter the results are presented. Each figure is explained and unexpected results are discussed where necessary. The chapter is divided in steps, parallel to the applied methods. Step 1 contains the rainfall analysis. In step 1a, the results of the rainfall analysis, with the presentation of the historic rainfall, the nowcasted rainfall, the results of the underestimation, the BIAS, the SE and the COR maps and graphs, can be found for the rainfall event of 13 October 2013. In step 1b, the rainfall analysis of 28 July 2014 is found and in 1c the analysis of 30 May 2016. In 1d, the rainfall events are compared. In step 1e, the results of the influence of the rainfall intensity on the performance are presented. In step 2, the results of the maximum lead time are presented for the three events. Finally, In step 3 and 4, the results of the 3Di modelling are presented.

4.1 Rainfall analysis in FEWS

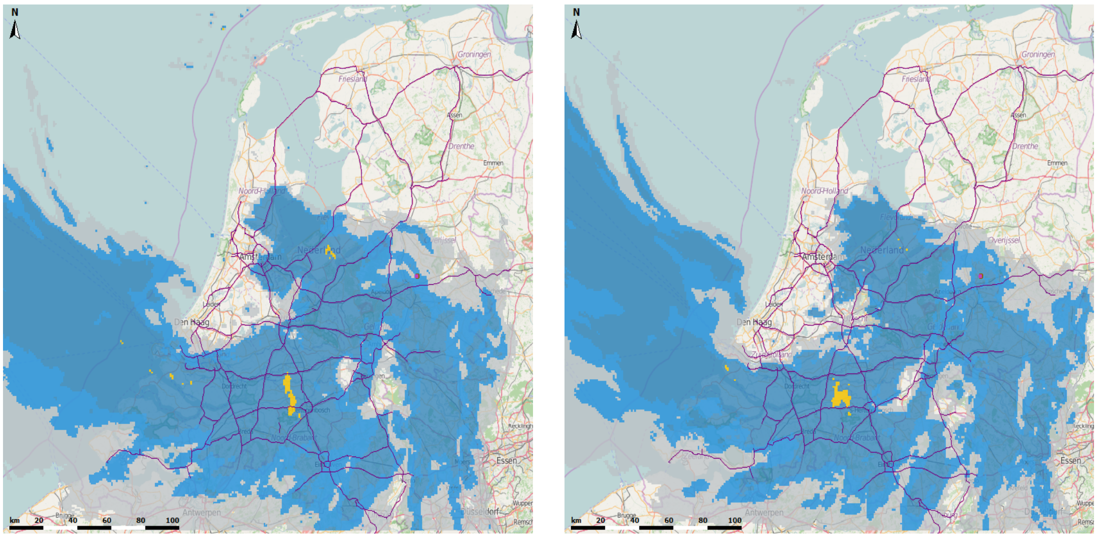
a Results step 1a: Rainfall analysis 2013

Observations rainfall maps
The maps of the historic rainfall and nowcasted rainfall on 13 October 2013 are presented in figure 4.1. As explained in chapter 3, the rainfall is the result of a cold front. The rainfall persists for almost 24 hours and has few extremes. At first sight, the pattern of the nowcasted rainfall resembles the historic rainfall for all three lead times. However, if looked closely at the regions, the precision decreases for longer lead times. The NC5min (top right), resembles the historic rainfall (top left) more, than the NC30min (lower left), which in turn resembles the historic rainfall and NC5min more than the NC1h (lower right).

Historic rainfall and nowcasted rainfall on 13 October 2013, 09h05



((A)) Historic rainfall-09h05 ((B)) Nowcast-5 minutes lead time



((C)) Nowcast-30 minutes lead time ((D)) Nowcast-1 hour lead time

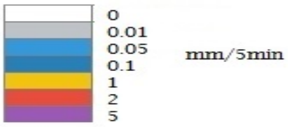


FIGURE 4.1: Results historic rainfall and nowcasted rainfall on 13 October 2013. At 09h05, the clearest rainfall intensity pattern was detected.

Moreover, the intensity of the historic rainfall is higher than predicted. This can be seen by comparing the colours in the maps with the legend. A red/purple colour means a very high intensity rainfall, of which there is more in the historic rainfall map than the nowcasted maps.

Calculation underestimation

This underestimation of the nowcast is computed below in table 4.1. The time period varies, as the time and duration of the event differs per location.

	Rainfall in mm/5min	Netherlands (20-18h)	Maassluis (21-18h)	Amsterdam (6-18h)	Purmerend (7-18h)
Historic rainfall	Sum	27.14	89.724	36.898	36.093
	Mean	0.102	0.355	0.248	0.267
	Max	0.211 (10h10)	2.780 (01h35)	0.833 (11h40)	1.691 (12h05)
Nowcast	Sum	14.383	38.82	20.211	26.059
	Mean	0.054	0.153	0.136	0.193
	Max	0.111 (10h15)	0.828 (02h15)	0.643 (11h40)	1.342 (12h00)
Underestimation	Sum	27.14/14.383 = **1.9x less**	89.724/38.82 = **2.3x less**	36.898/20.211 = **1.8x less**	36.093/26.059 = **1.4x less**
	Mean	0.102/0.054 = **1.9x less**	0.355/0.153 = **2.3x less**	0.248/0.136 = **1.8x less**	0.267/0.193 = **1.4x less**
	Max	0.211/0.111 = **1.9x less**	2.78/0.828 = **3.3x less**	0.833/0.643 = **1.3x less**	1.691/1.342 = **1.3x less**

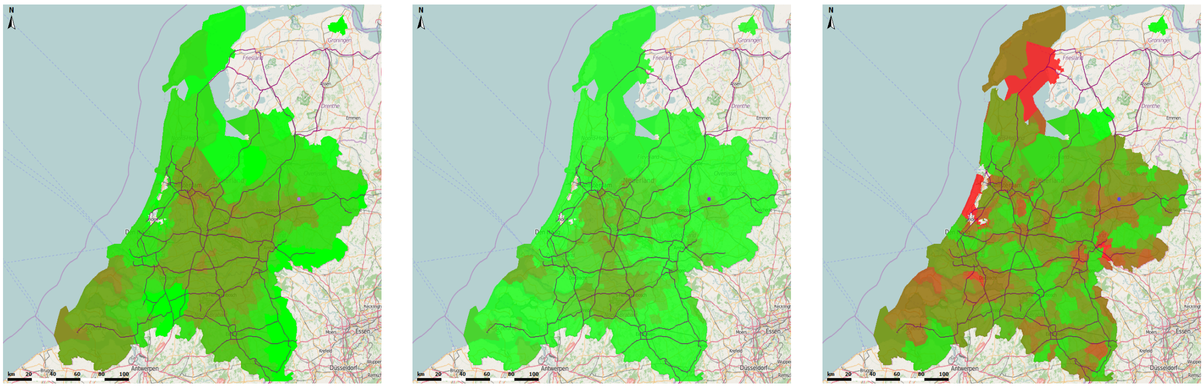
TABLE 4.1: Results calculation underestimation of the nowcast.

The sum, mean and maximum of the rainfall are calculated for the mean region value. The nowcasts underestimate the historic rainfall 1.3 to 3.3 times. In other words, the amount of nowcasted rainfall is 30-75% of the actual measured values. There is quite a difference between the average value of the Netherlands and an area that has a high intensity rainfall. What is more, there is quite a difference between the underestimation of rainfall in Maassluis and in Purmerend.

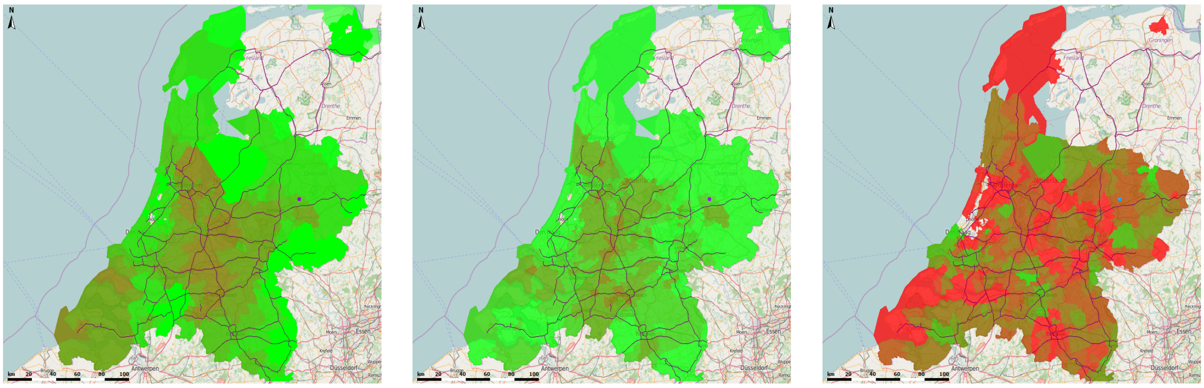
Observations performance maps

In figure 4.2 the BIAS, SE and COR maps are presented for different lead times: 5 minutes (top), 30 minutes (middle) and 1 hour (bottom). The maps of BIAS, SE and COR have a different legend, but for all three applies: the greener, the better the performance of the nowcast.

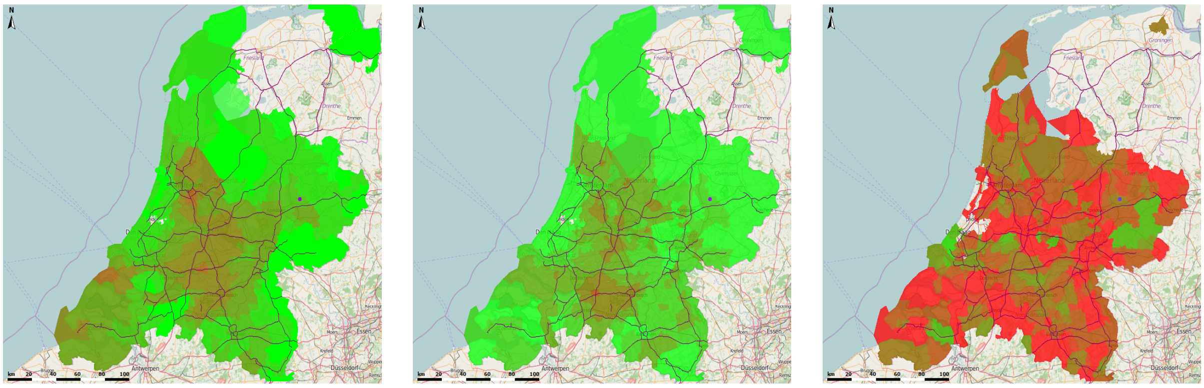
BIAS *SE* *COR*



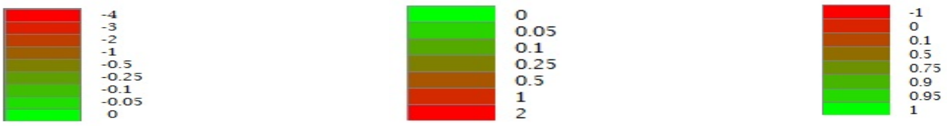
((a)) BIAS-5min ((b)) SE-5min ((c)) COR-5min



((d)) BIAS-30min ((e)) SE-30min ((f)) COR-30min



((g)) BIAS-1hour ((h)) SE-1hour ((i)) COR-1hour



((j)) Legend BIAS ((k)) Legend SE ((l)) Legend COR

FIGURE 4.2: Results BIAS, SE and COR on 09h05, 13 October 2013. The BIAS, SE and COR between the historic rainfall and nowcasts with lead time 5 minutes, 30 minutes and 1 hour are determined for different subregions in the Netherlands.

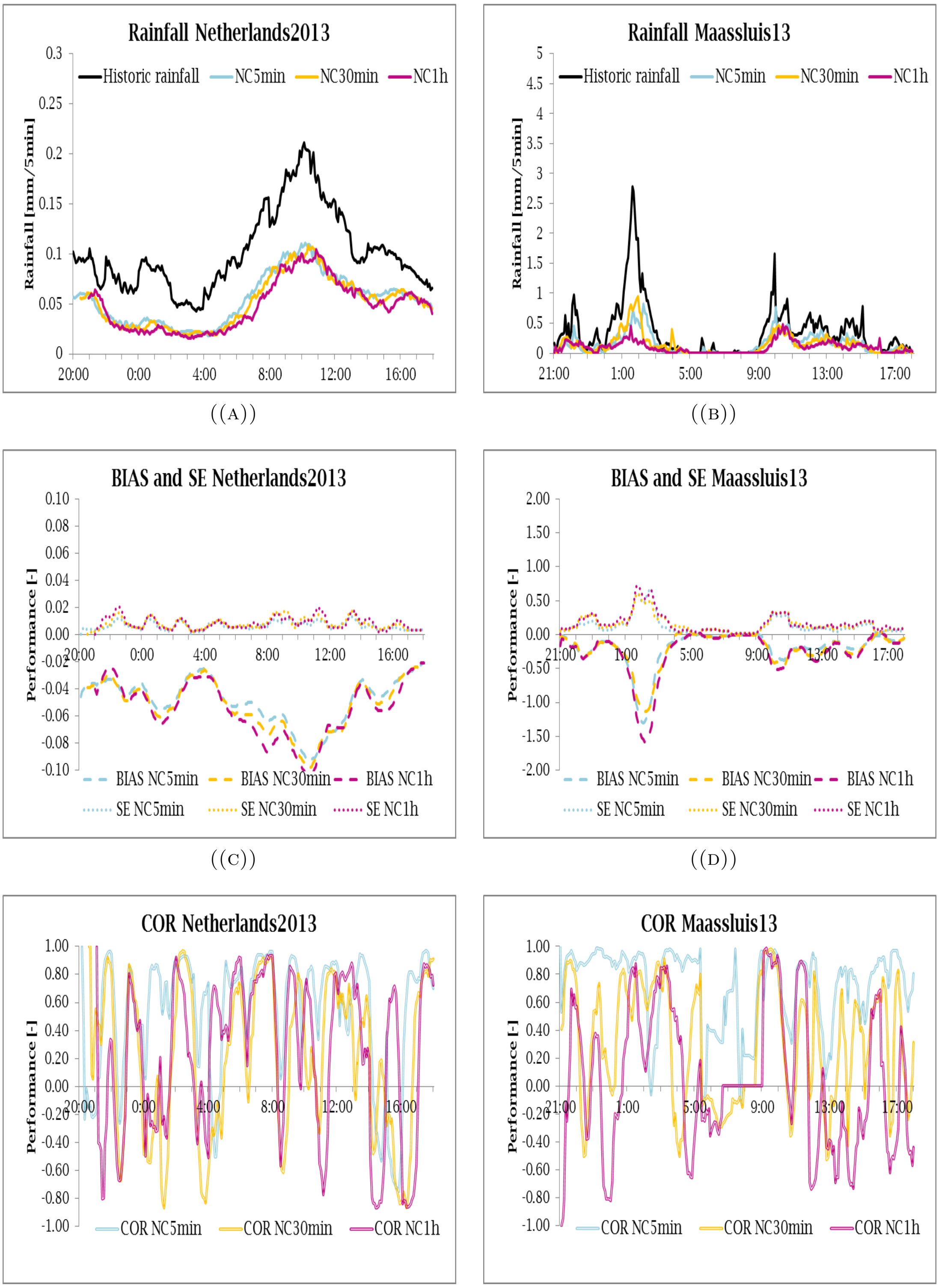
The first observation of figure 4.2 is that for the BIAS and SE maps the worst performance (i.e. lower BIAS and higher SE) is found in the middle part of the Netherlands and Zeeland. The red pattern almost coincides with the high rainfall pattern in figure 4.1. This means that, at least for this event, the nowcasts perform less at high rainfall intensities. Regarding the COR, this relationship is not found, at least not by analysing the maps. The high rainfall parts have a low COR, but also other regions have a low COR.

The second observation is that the performance decreases rapidly if the lead time increases for the COR, and to a lesser extent the BIAS and SE. This can be seen in 4.2 by the increase of red for longer lead times. For the COR and the SE the area of red increases, and for the BIAS the red becomes solely more intense. The area with a relatively good BIAS and SE does not decrease by much.

Observations graphs
Figure 4.3 shows the historic rainfall, nowcasted rainfall, BIAS, SE and COR averaged over the Netherlands and Maassluis for 3 lead times: 5 minutes (blue), 30 minutes (yellow) and 1 hour (purple). The graphs of Amsterdam and Purmerend can be found in appendix 4. The scales of figure 4.3BD are different from 4.3AC, as the rainfall in Maassluis was more extreme. For the other events, the scales are the same (i.e. all graphs of the Netherlands have the same scales and all graphs of the cities have the same scales).

Observing the graphs of rainfall in the Netherlands (A), it can be seen that at the maximum historic rainfall, the nowcasts show also a maximum, though underestimated. The BIAS (C) is the lowest at that point. The SE and COR vary considerably, but the shortest lead time has almost the entire time the best performance. For the NC5min, the minimum BIAS is -0.093, the maximum SE is 0.014 and the mean COR is 0.523.

Observing the graphs of rainfall in Maassluis (B), it can be seen that the nowcasts are underestimating the historic rainfall noticeably. The NC5min and NC30min are catching a small peak, where the historic rainfall results in a high peak at around 02h00. The NC1h only appears to have a small bump, indistinguishable from the other small bumps. The BIAS and SE (D) of all lead times show peaks just after the historic rainfall peak. The BIAS becomes worse for higher lead times, but the SE does not increase by much. The COR (F) becomes clearly lower for higher lead times. For the NC5min, the minimum BIAS is -1.3, the maximum SE is 0.667 and the mean COR is 0.713.

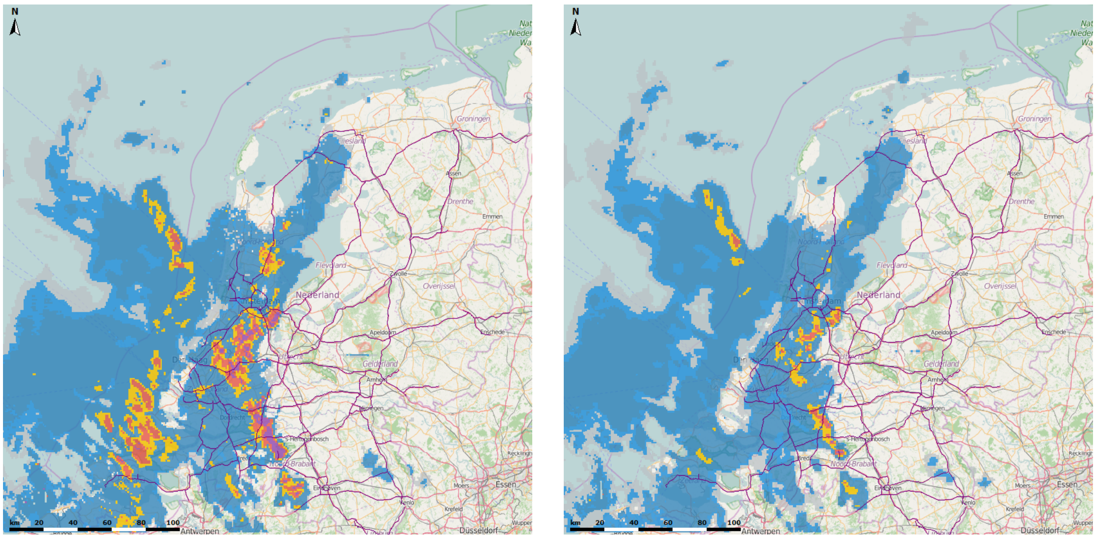


((A)) ((B)) ((C)) ((D)) ((E)) ((F))

Figure 4.3: The historic rainfall, nowcasted rainfall, BIAS, SE and COR averaged over the Netherlands and Maassluis from 12 October 2013 - 13 October 2013.

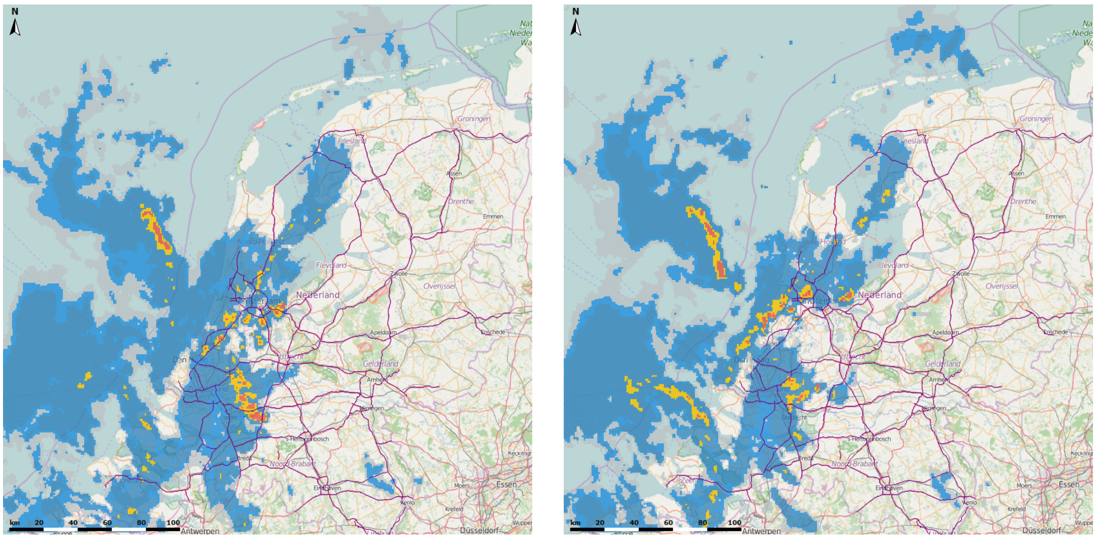
b Results step 1b: Rainfall analysis 2014

Historic rainfall and nowcasted rainfall on 28 July 2014, 09h00



((A)) Historic rainfall-09h00

((B)) Nowcast-5 minutes lead time



((C)) Nowcast-30 minutes lead time

((D)) Nowcast-1 hour lead time

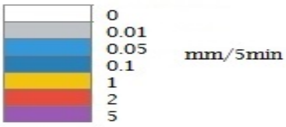


FIGURE 4.4: Results historic rainfall and nowcasted rainfall on 28 July 2014. At 09h00, the highest rainfall intensity was detected on average.

Observations rainfall maps

In figure 4.4 the maps of the historic rainfall and nowcasted rainfall are presented for 28 July 2014 at 09h00, at its maximum. As explained in chapter 3, the cloudburst mostly affected the western part of the Netherlands. While the pattern of the nowcasted rainfall resembles the historic rainfall for all three lead times, it is clear that the resemblance decreases with a higher lead time. The intensity of the historic rainfall is again higher than predicted.

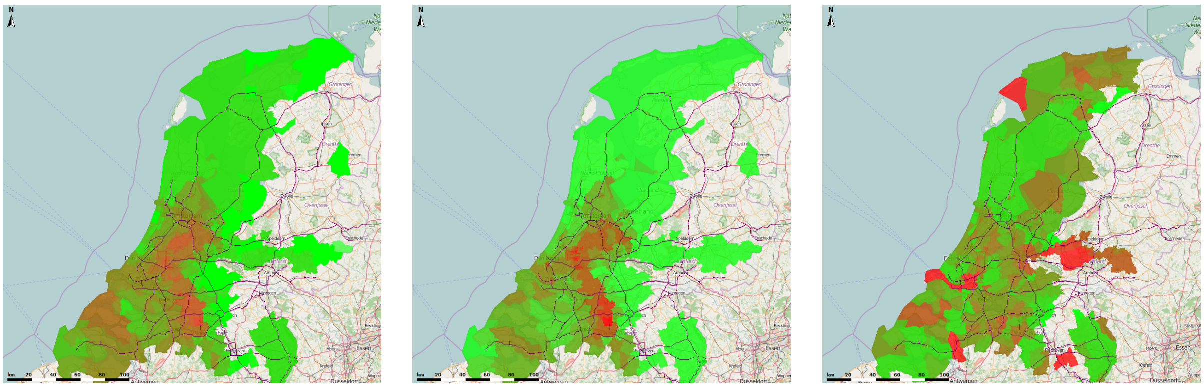
Calculation underestimation

Below in table 4.2, the results of the calculation of this underestimation of the nowcasts during the rainfall on the 28^{th} of July 2014 are presented. The sum, mean and maximum of the rainfall are calculated for the mean region value. Since the rainfall intensity is much higher during that period in Alphen aan de Rijn, Amsterdam and Urk than average parts in the Netherlands, the sum, mean and maximum become also higher. The nowcasts underestimate the historic rainfall 2.0 to 2.7 times. In other words, the amount of nowcasted rainfall is 40-50% of the actual measured values. There is almost no difference between the average underestimation over the Netherlands and an area that has a high intensity rainfall. As the BIAS gives information about systematic errors, and underestimation being a systematic error, this could be corrected for. The results of this underestimation are therefore included in the 3Di modelling in step 3.

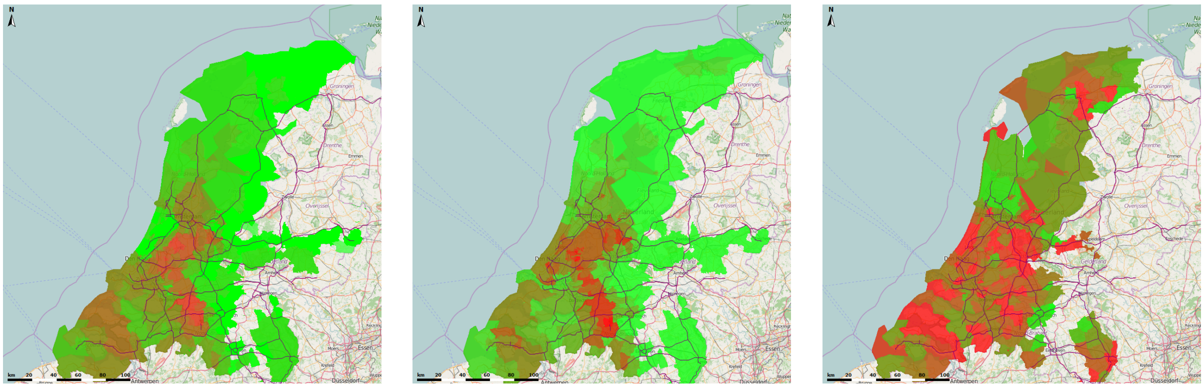
	Rainfall in mm/5min	Netherlands (2-16h)	Alphen aan de Rijn (7-13h)	Amsterdam (8-12h)	Urk (2h40-4h10)
Historic rainfall	Sum	10.124	71.837	45.819	36.994
	Mean	0.135	0.958	0.628	1.233
	Max	0.227 (9h00)	3.438 (8h05)	2.06 (10h05)	5.897 (3h50)
Nowcast	Sum	4.391	34.44	19.988	14.351
	Mean	0.059	0.459	0.274	0.495
	Max	0.083 (9h00)	1.681 (7h55)	1.013 (9h40)	2.680 (3h50)
Under-estimation	Sum	10.124/4.391 = **2.3x less**	71.837/34.44 = **2.1x less**	45.819/19.988 = **2.3x less**	36.994/14.351 = **2.6x less**
	Mean	0.135/0.059 = **2.3x less**	0.958/0.459 = **2.1x less**	0.628/0.274 = **2.3x less**	1.233/0.495 = **2.5x less**
	Max	0.227/0.083 = **2.7x less**	3.438/1.681 = **2.0x less**	2.056/1.013 = **2.0x less**	5.897/2.680 = **2.2x less**

TABLE 4.2: Results calculation underestimation of the nowcast.

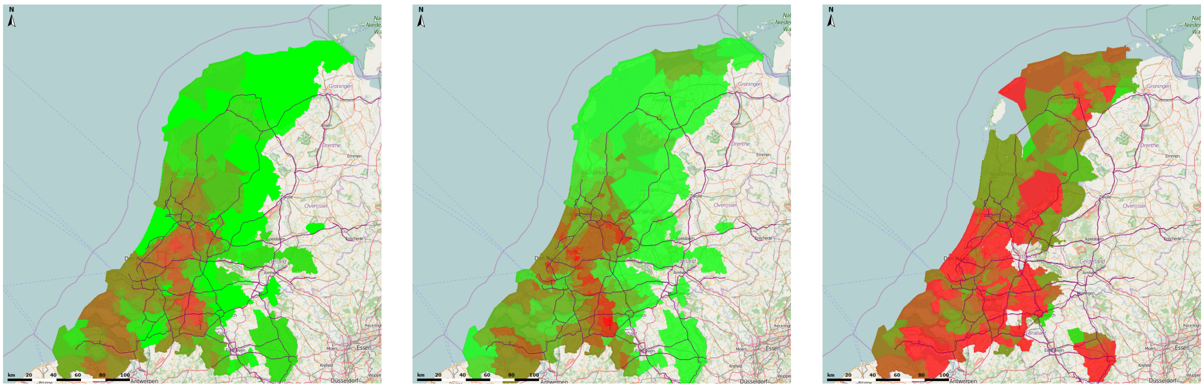
BIAS *SE* *COR*



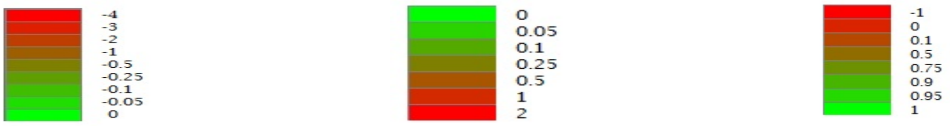
((A)) BIAS-5min ((B)) SE-5min ((C)) COR-5min



((D)) BIAS-30min ((E)) SE-30min ((F)) COR-30min



((G)) BIAS-1hour ((H)) SE-1hour ((I)) COR-1hour



((J)) Legend BIAS ((K)) Legend SE ((L)) Legend COR

FIGURE 4.5: Results BIAS, SE and COR on 09h00, 28 July 2014. The BIAS, SE and COR between the historic rainfall and nowcasts with lead time 5 minutes, 30 minutes and 1 hour are determined for different subregions in the Netherlands.

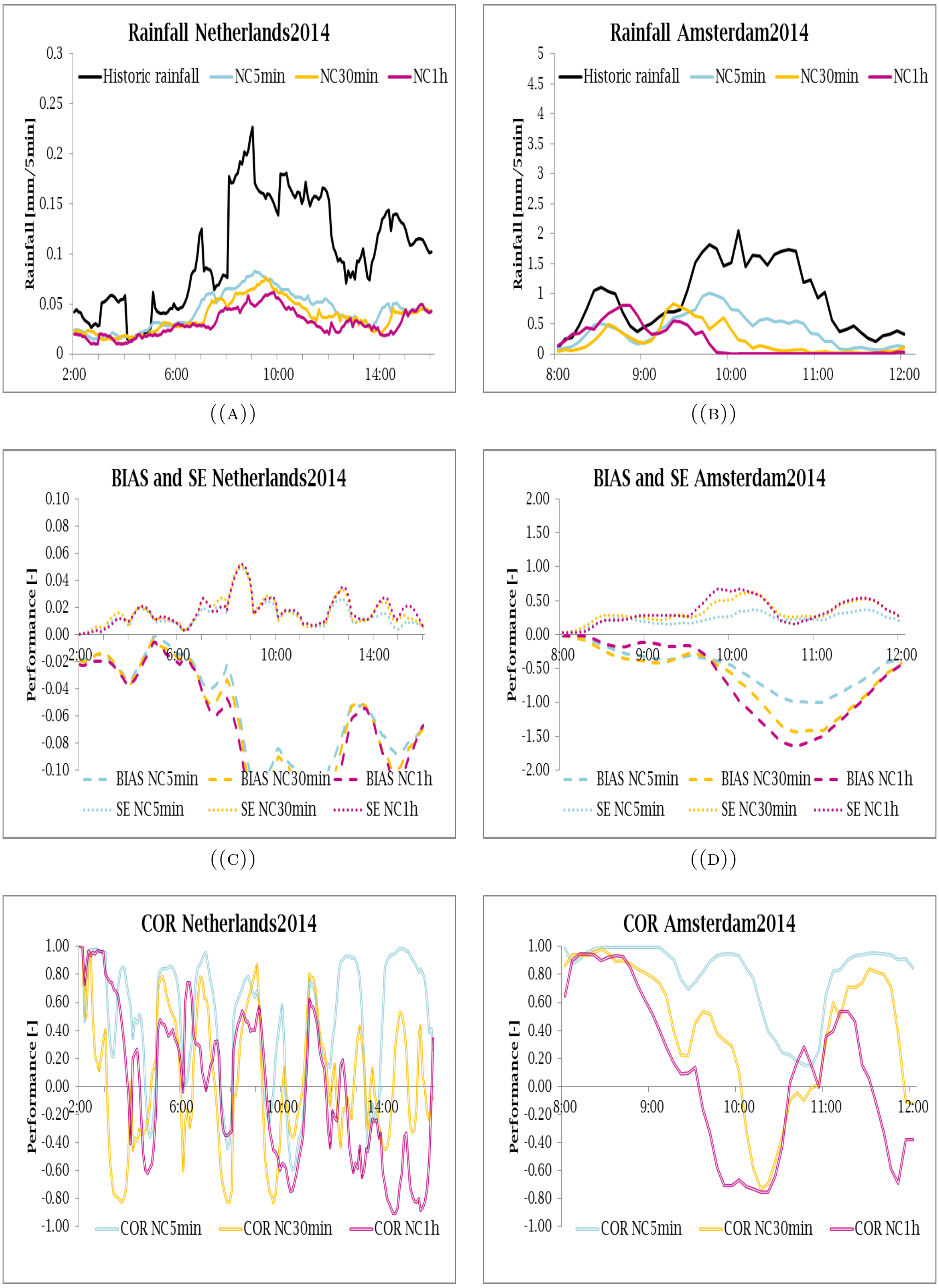
Observations performance maps
In figure 4.5 the BIAS, SE and COR maps are presented for different lead times: 5 minutes (top), 30 minutes (middle) and 1 hour (bottom). The first observation of figure 4.5 is that for the BIAS and SE maps the worst performance is found at the highest rainfall location. The red pattern almost coincides with the high rainfall pattern in figure 4.4. This means that, also for this event, the nowcasts perform less at high rainfall intensities. Regarding the COR, this relationship is not so clear.

The second observation is that the performance decreases rapidly if the lead time increases for the COR, and to a lesser extent for the BIAS and SE, which was also true for 2013. For the COR the area of red increases, and for the BIAS and SE the red becomes solely more intense. The area with a relatively good BIAS and SE does not decrease. What is more, the bright green areas become even more abundant for the BIAS for the NC1h, which is unexpected.

Observations graphs
Figure 4.6 shows the historic rainfall, nowcasted rainfall, BIAS, SE and COR averaged over the Netherlands and Amsterdam for 3 lead times: 5 minutes, 30 minutes and 1 hour. The graphs of Alphen aan de Rijn and Urk can be found in appendix 4.

Observing the graphs of rainfall in the Netherlands (A), it can be seen that the underestimation is also visible here. The peak at 8h00-12h00 is not so clear in the nowcasts. The peak coincides with a lower BIAS and higher SE (C) for all three lead times, although the separation of the lead times is more clear in the BIAS. The COR (E) does not show this relationship, but does show an overall better COR of the historic rainfall with the NC5min than with the other nowcasts. The spread of the difference per lead time differs depending on the time and thus amount of rainfall. For the NC5min, the minimum BIAS is -0.118, the maximum SE is 0.05 and the mean COR is 0.5707.

Observing the graphs of rainfall in Amsterdam (B), it can be seen that the nowcasts again underestimate the historic rainfall, but follow the same pattern. The pattern of the nowcasts coincides less with the historic rainfall at higher lead times. This is quite clear by looking at the COR (F). NC5min has the highest COR for almost the entire period. The BIAS (D) shows a clear dip at 10h45. This is not exactly at the maximum of the rainfall, but lags a minute or 30 behind. The SE (D) has two bumps, the first, biggest one at the maximum value of the historic rainfall. The second one can not be explained by solely comparing it to the historic rainfall and nowcasts. For the NC5min the minimum BIAS is -1.003, the maximum SE is 0.367 and the mean COR is 0.797.



((A)) ((B))

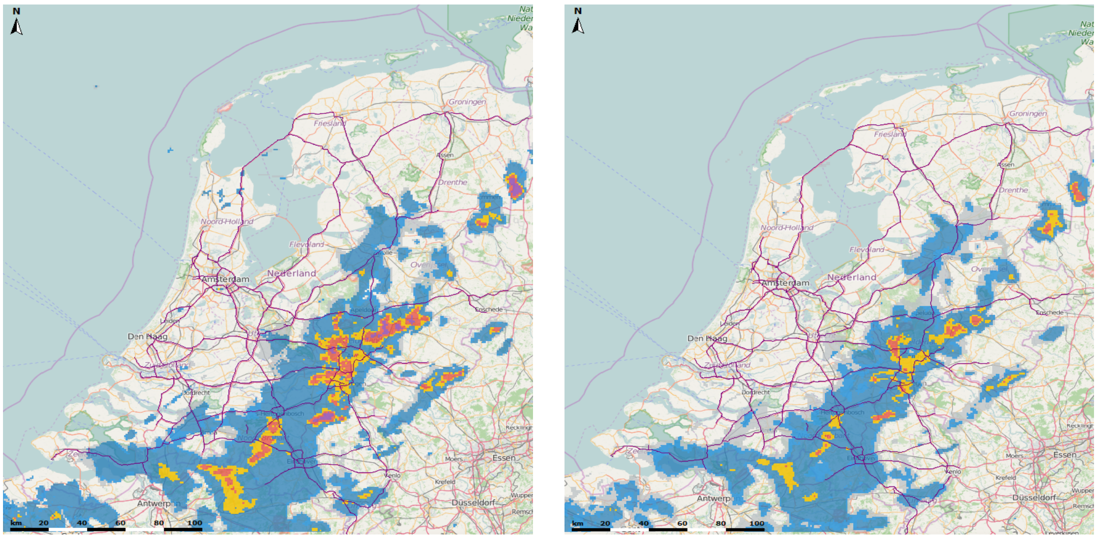
((C)) ((D))

((E)) ((F))

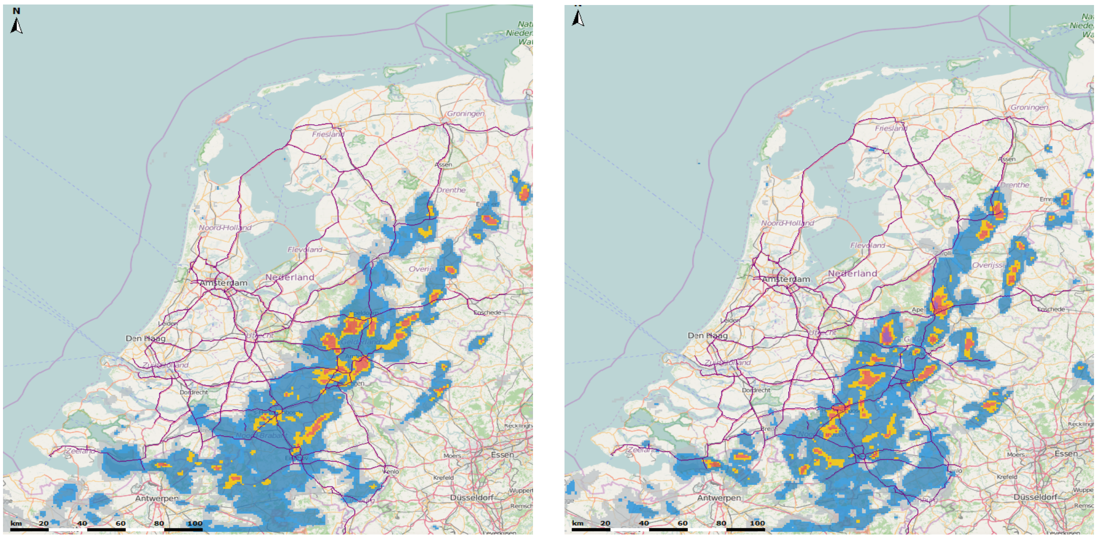
FIGURE 4.6: The historic rainfall, nowcasted rainfall, BIAS, SE and COR averaged over the Netherlands and Amsterdam on 28 July 2014.

c Results step 1c: Rainfall analysis 2016

Historic rainfall and nowcasted rainfall on 30 May 2016, 18h00



((A)) Historic rainfall-18h00 ((B)) Nowcast-5 minutes lead time



((C)) Nowcast-30 minutes lead time ((D)) Nowcast-1 hour lead time

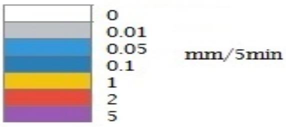


FIGURE 4.7: Results historic rainfall and nowcasted rainfall on 30 May 2016. At 18h00, the highest rainfall intensity was detected on average.

Observations rainfall maps

In figure 4.7 the maps of the historic rainfall and nowcasted rainfall are presented, for the rainfall event on 30 May 2016 at 18h00, at its maximum. As explained in chapter 3, the rainfall was mostly focused on the southeastern part of the Netherlands. While the pattern of the nowcasted rainfall resembles the historic rainfall for all three lead times, it is clear that the resemblance decreases with a higher lead time. The high intensity area around Apeldoorn is not present in the NC1h.

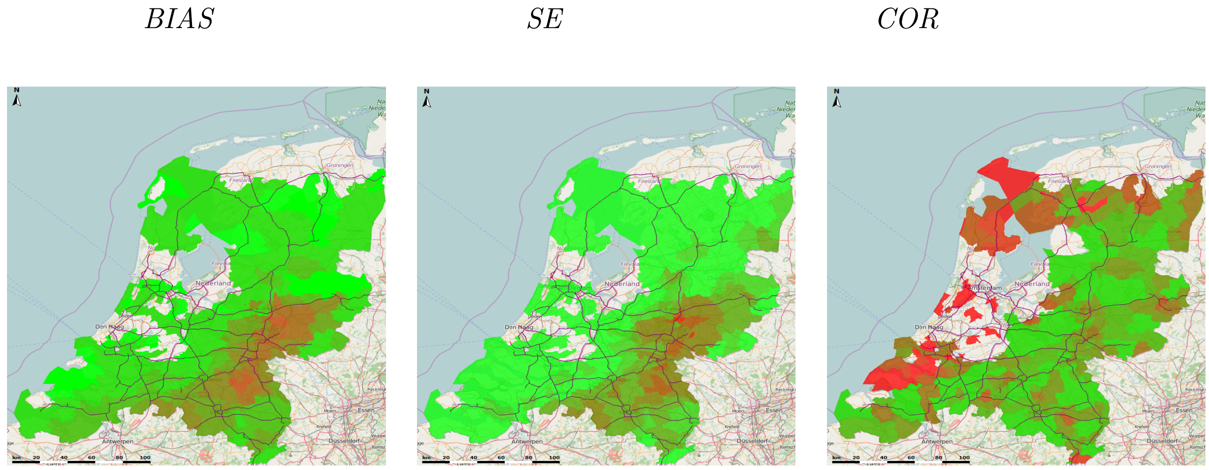
Calculation underestimation

Below in table 4.3, the results of this calculation of the underestimation of the nowcasts during rainfall on the 30th of May 2016 are presented. The sum, mean and maximum of the rainfall are calculated for the mean region value. The nowcasts underestimate the historic rainfall 1.4 to 2.3 times. In other words, the amount of nowcasted rainfall is 40-70% of the actual measured values. There is almost no difference between the average value of the Netherlands and Enschede, which experienced a high intensity rainfall. The underestimation is larger in Arnhem and Zutphen.

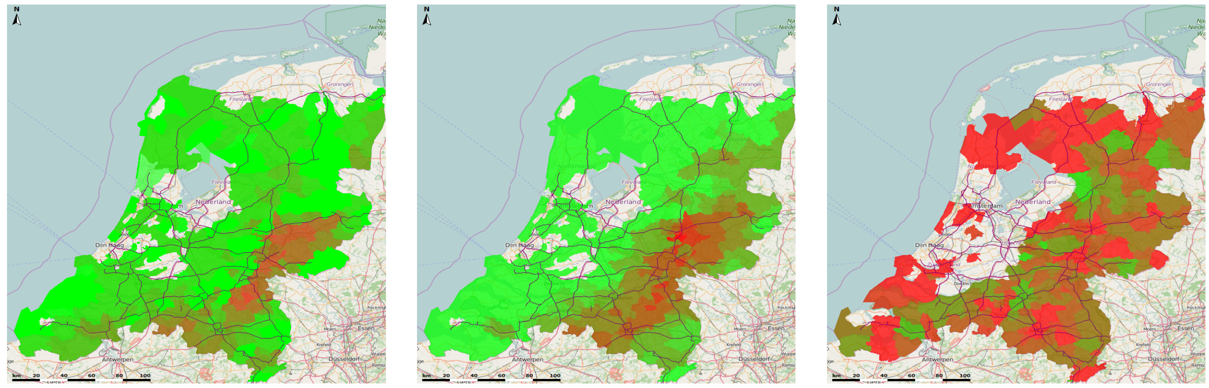
	Rainfall in mm/5min	Netherlands (16h-21h)	Arnhem (16h30-21h30)	Enschede (18h30-20h30)	Zuthpen (16h-21h)
Historic rainfall	Sum	10.271	46.695	22.458	59.992
	Mean	0.166	0.753	0.864	0.983
	Max	0.218 (17h25)	3.745 (18h10)	3.640 (19h00)	4.287 (16h55)
Nowcast	Sum	6.464	20.654	13.085	26.703
	Mean	0.104	0.382	0.503	0.438
	Max	0.156 (20h15*)	1.653 (20h05*)	2.216 (19h00)	2.015 (16h55)
Under-estimation	Sum	10.271/6.464 = **1.6x less**	46.695/20.654 = **2.3x less**	22.458/13.085 = **1.7x less**	59.992/26.703 = **2.2x less**
	Mean	0.166/0.104 = **1.6x less**	0.753/0.382 = **2.0x less**	0.864/0.503 = **1.7x less**	0.983/0.438 = **2.2x less**
	Max	0.218/0.156 = **1.4x less**	3.745/1.653 = **2.3x less**	3.640/2.216 = **1.6x less**	4.287/2.015 = **2.1x less**

TABLE 4.3: Results calculation underestimation of the nowcast.

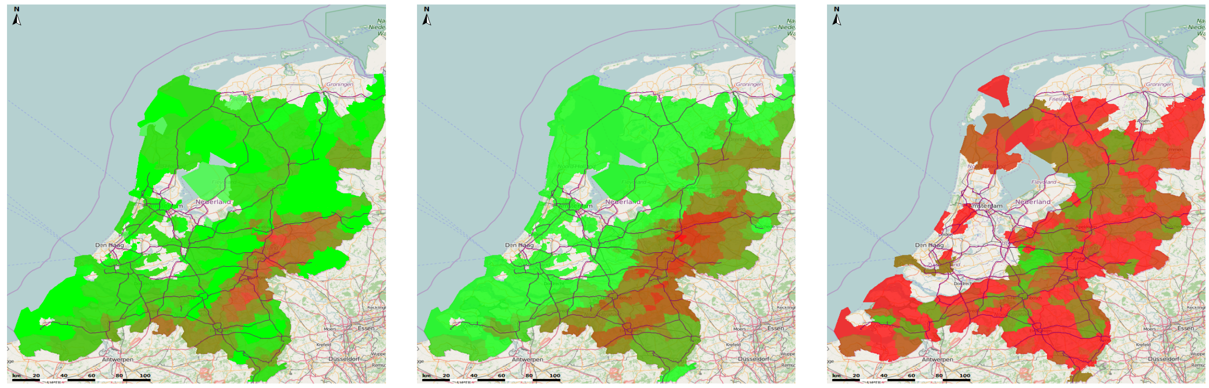
*The maximum of the historic rainfall is at a different moment than the maximum of the nowcasted rainfall.



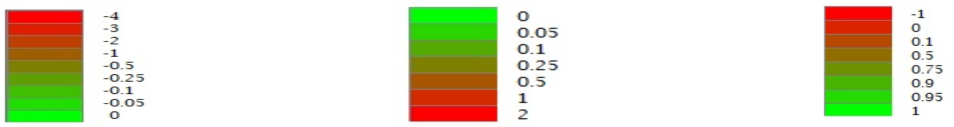
((a)) BIAS-5min ((b)) SE-5min ((c)) COR-5min



((d)) BIAS-30min ((e)) SE-30min ((f)) COR-30min



((g)) BIAS-1hour ((h)) SE-1hour ((i)) COR-1hour



((j)) Legend BIAS ((k)) Legend SE ((l)) Legend COR

Figure 4.8: Results BIAS, SE and COR on 18h00, 30 May 2016. The BIAS, SE and COR between the historic rainfall and nowcasts with lead time 5 minutes, 30 minutes and 1 hour are determined for different subregions in the Netherlands.

Observations performance maps

In figure 4.8 the BIAS, SE and COR maps are presented for different lead times: 5 minutes (top), 30 minutes (middle) and 1 hour (bottom). The first observation of figure 4.8 is that for the BIAS and SE maps the worst performance is found at the highest rainfall location. The red pattern almost coincides with the high rainfall pattern in figure 4.7. This means that, also for this event, the nowcasts perform less at high rainfall intensities. Regarding the COR, this relationship is not found.

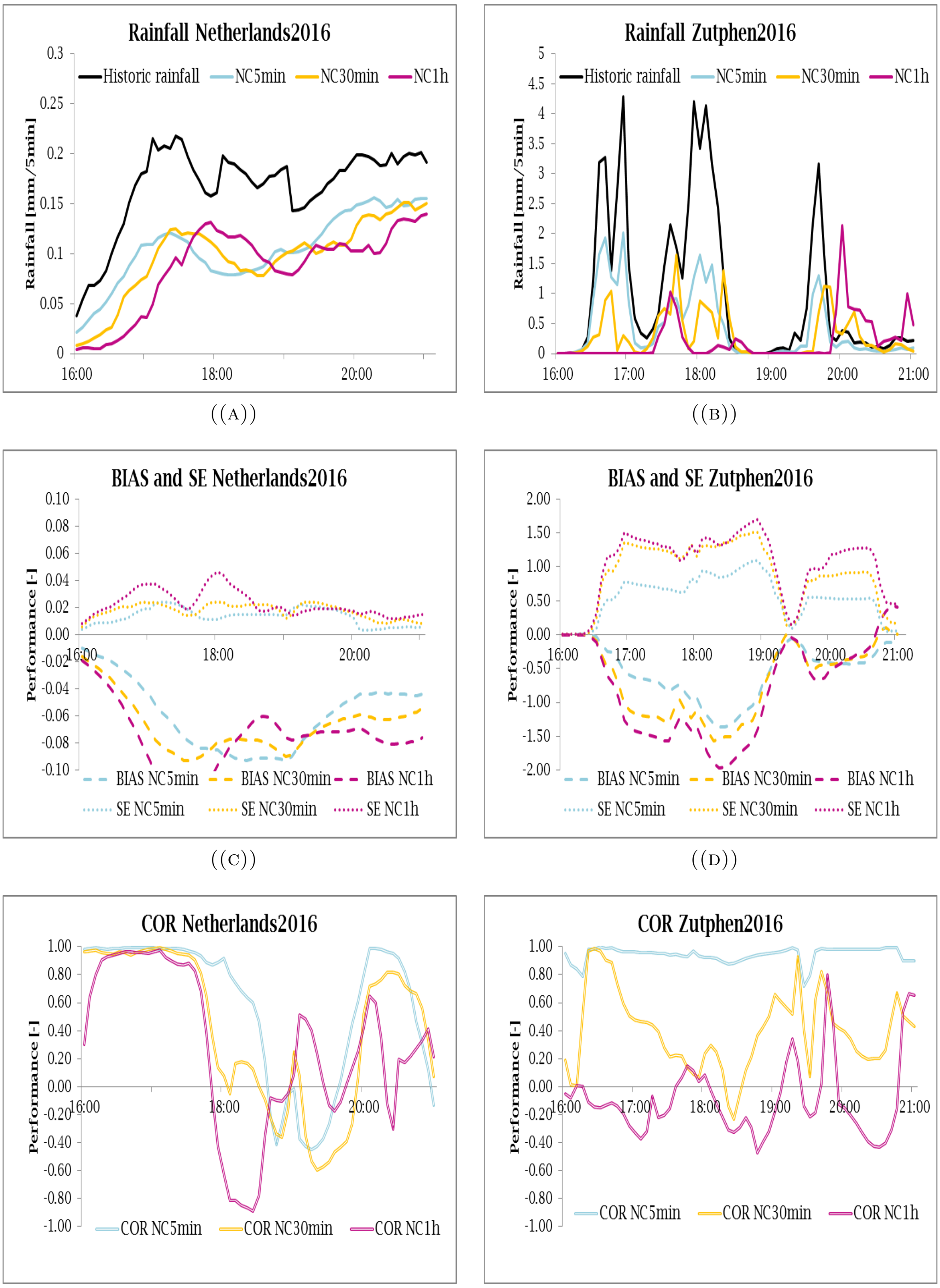
The second observation is that the performance decreases rapidly if the lead time increases for the COR, and to a lesser extent for the BIAS and SE, which was also true for 2013 and 2014. For the COR the area of red increases, and for the BIAS the red becomes solely more intense. The area of red in the SE increases from NC5min to NC30min, but after that, the area with a relatively good BIAS and SE does not decrease. What is more, the bright green areas become even more abundant for the BIAS for the NC30min and NC1h, which is unexpected.

Observations graphs

Figure 4.9 shows the historic rainfall, nowcasted rainfall, BIAS, SE and COR averaged over the Netherlands and Zutphen for 3 lead times: 5 minutes, 30 minutes and 1 hour. The graphs of Arnhem and Enschede can be found in appendix 4.

Observing the graphs of rainfall in the Netherlands (A), it can be seen that the underestimation is visible here as well. From this graph it is clear that the performance is not always necessarily better for shorter lead times. For the NC5min, the minimum BIAS is -0.093, the maximum SE is 0.024 and the mean COR is 0.582.

Observing the graphs of rainfall in Zutphen (B), it can be seen that the nowcasts again underestimate the historic rainfall, but follow the same pattern. There are three peaks present in the historic rainfall. The NC5min and NC30min catch all three. The NC1h misses the first one, and is half an hour too late in the last one. The maximum of the NC1h on the other hand is more similar to the historic rainfall compared to NC5min and NC30min. The BIAS and SE (D) are largest for the second peak, then for the first peak and lastly in the last peak. The NC5min performs very well in terms of COR (F). The COR's of NC30min and NC1h are substantially lower. For the NC5min the minimum BIAS is -1.367, the maximum SE is 1.101 and the mean COR is 0.940.



((A)) ((B))

((C)) ((D))

((E)) ((F))

FIGURE 4.9: The historic rainfall, nowcasted rainfall, BIAS, SE and COR averaged over the Netherlands and Zutphen on 30 May 2016.

d Results step 1d: Comparison rainfall analysis 2013, 2014 and 2016

The results of the rainfall analysis of the 2013, 2014 and 2016 events show some similarities, but also differences. The first similarity is that if the lead time is longer, the performance of the nowcasts generally decreases. The second similarity is that usually the performance of the nowcasts also decreases at high rainfall intensities. The third similarity is that the nowcasts of all three events underestimate the historic rainfall. However, the first difference is that the underestimation of 2013 was more variable: 1.3-3.3 times smaller as opposed to 2-2.7 times smaller in 2014 and 1.4-2.3 times smaller in 2016. Moreover, the SE and BIAS are smallest in 2016, followed by 2013, and substantially larger in 2014. The COR between the historic rainfall and the NC5min over the Netherlands is slightly better in 2016 (0.58) than in 2014 (0.57) and 2013 (0.52).

e Results step 1e: Performance nowcast per rainfall intensity

Lastly, the performance of the nowcasts are compared for different rainfall intensities. We compare a shower with a rainfall intensity of 5-10 mm per hour (Amsterdam and Purmerend 2013), 10-15 mm per hour (Maassluis 2013), 15-20 mm per hour (Enschede 2016), 20-25 mm hour (Amsterdam 2014 and Arnhem 2016) and 25-30 mm per hour (Alphen aan de Rijn 2014 and Zutphen 2016). These are the maximum rainfall experienced, averaged over the regions. The mean BIAS, SE and COR between the historic rainfall and the NC5min are found in appendix 5.

Following from the data, the absolute BIAS and SE increase with rainfall intensity, which also did appear from the maps in figure 4.2, 4.5 and 4.8. The trend is presented in figure 4.10. The COR does not decrease for longer lead times, which was also not found in figure 4.2, 4.5 and 4.8.

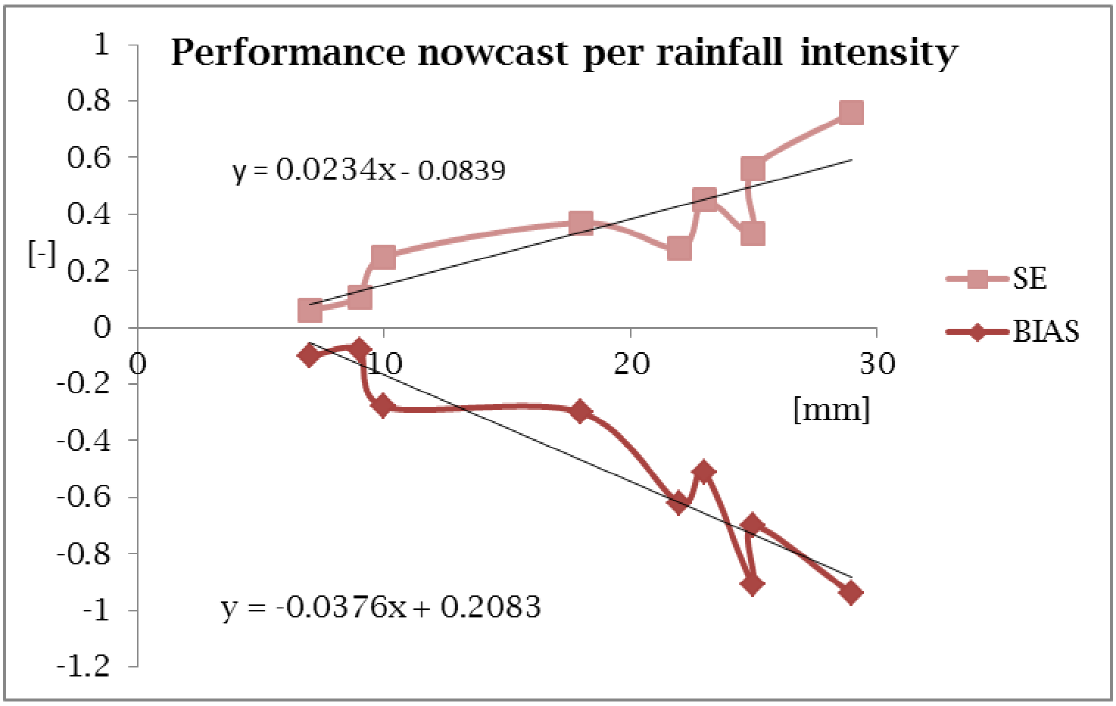


FIGURE 4.10: The BIAS and SE between NC5min and historic rainfall per maximum rainfall intensity sum.

The SE increases with 2% per 1mm rainfall increase per hour; the BIAS decreases with 4% per 1mm increase.

4.2 Results step 2: Maximum lead time

The complete computation of the maximum lead time is found in appendix 6.

The maximum acceptable lead times are (table 4.4, table 4.5 and 4.6):

Location	BIAS	SE	COR
NL	>1h	30min	>1h
Maassluis	30min	5min	15min
Amsterdam	25min	5min	10min
Purmerend	5min	5min	5min
Averaged over the regions	20min	5min	10min

TABLE 4.4: Maximum lead time 2013.

Location	BIAS	SE	COR
NL	50min	35min	>1h
Alphen aan de Rijn	20min	20min	10min
Amsterdam	15min	10min	25min
Urk	30min	10min	10min
Averaged over the regions	22min	13min	15min

Table 4.5: Maximum lead time 2014.

Location	BIAS	SE	COR
NL	>1h	>1h	>1h
Arnhem	50min	25min	20min
Enschede	25min	20min	10min
Zutphen	50min	20min	5min
Averaged over the regions	42min	22min	12min

Table 4.6: Maximum lead time 2016.

For the Netherlands as a whole, the results are averaged out. This means that the nowcast with a lead time of 1 hour can still be considered adequate for the three events. Averaged over the regions Maassluis, Amsterdam and Purmerend, the maximum lead time during the event of 13 October 2013 varies between 5-20 minutes. It would be 5 minutes if looked at the weakest link (in this case the SE). It would be 12 minutes if looked at the average value of the statistics.

Averaged over the regions Alphen aan de Rijn, Amsterdam and Urk, the maximum lead time during the event of 28 July 2014 varies between 13-22 minutes. It would be 13 minutes if looked at the weakest link (again the SE). It would be 17 minutes if looked at the average value of the statistics.

Averaged over the regions Arnhem, Enschede and Zutphen, the maximum lead time during the event of 30 May 2016 varies between 12-42 minutes. It would be 12 minutes if looked at the weakest link (in this case the COR). It would be 25 minutes if looked at the average value of the statistics.

The mean value of the statistics averaged over the regions and events is 18 minutes. The minimum value averaged over the regions and events is 10 minutes. The maximum value averaged over the regions and events is 28 minutes.

Therefore, the final answer of the maximum lead time is that it is 20(±10) minutes on a regional scale.

4.3 Results step 3: 3Di

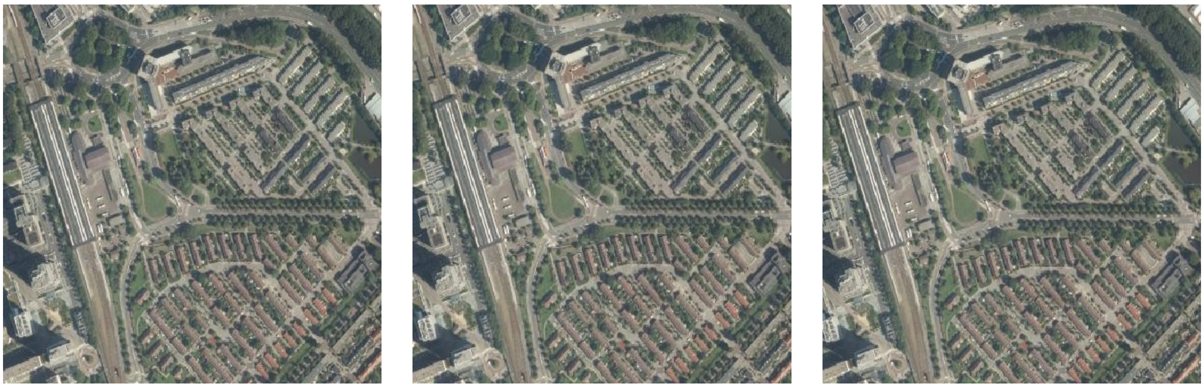
In figure 4.11, the inundation depths modelled by 3Di are shown. This is the maximum water height on street at any given time. The darker the blue, the higher the water is, up to 20 centimetres. In figure 4.11A, the results of the modelling with historic rainfall as input are shown. High inundation depths are found in Watergraafsmeer. In the nowcast simulations (Fig. 4.11CDE) there appeared to be no inundation. This is explained by the fact that the nowcasted rainfall is underestimating the historic rainfall. This means that the underestimation needs to be included.

In figure 4.11FGH, the results of this correction are shown. In this case, there definitely appears inundation. The inundation is, just as the historic simulation, mostly found in the Watergraafsmeer region. The 2xNC5min (Fig. 4.11F) resembles the historic simulation the best, then, surprisingly, 2xNC1h (Fig. 4.11H) and lastly, 2xNC30min (Fig. 4.11G). In order to explain this, the graphs of the nowcasted rainfall (Fig. 4.6B) are compared with the historic rainfall. It appears that the maximum of the NC1h is, although at a different time, higher than the maximum of the NC30min. This results also in higher inundation depths for the NC1h. This means that the nowcasted maximum rainfall is very important to determine the level of inconvenience or damage.

Now, for the timing of the events, it appeared that the maximum of the historic rainfall is at 197 minutes after the beginning of the rainfall event. The maximum of the 2xNC5min is at 157 minutes. The maximum of 2xNC30min is at 135 minutes and the NC1h at 90 minutes. Pictures of the water levels at these time steps are shown in appendix 7. At least for this event, the longer the lead time, the earlier the maximum inundation depths are expected. This is a result of the peak rainfall also being forecasted earlier. If it was the other way around (i.e. the longer the lead time the later the maximum inundation depths are reached), it would be more of a problem. A warning system would be too late.

((A)) Maximum inundation depth-historic rainfall as input

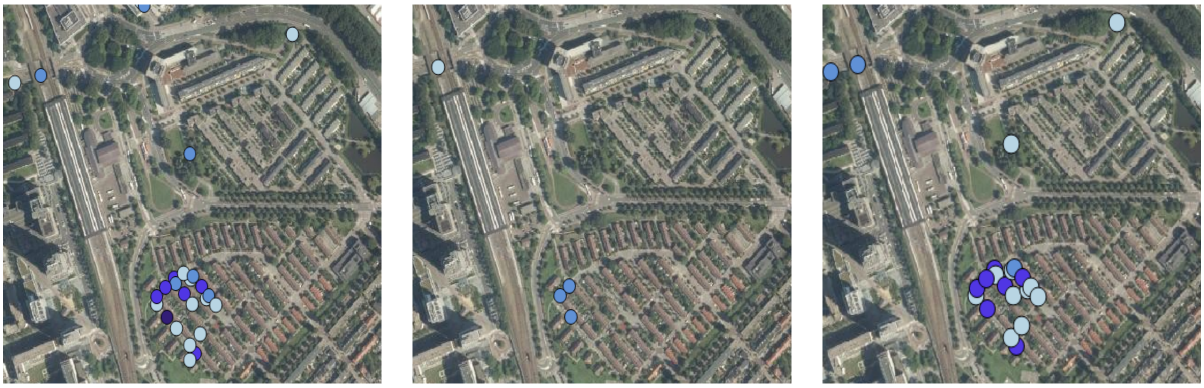
((B)) Legend



((C)) Maximum inundation depth-NC5min

((D)) Maximum inundation depth-NC30min as input

((E)) Maximum inundation depth-NC1h as input



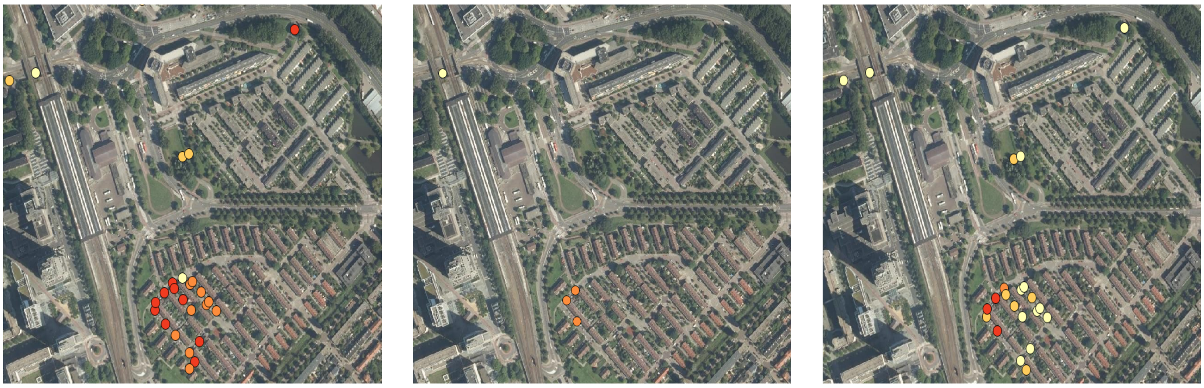
((F)) Maximum inundation depth-2xNC5min

((G)) Maximum inundation depth-2xNC30min

((H)) Maximum inundation depth-2xNC1h

FIGURE 4.11: Results 3Di modelling - The maximum inundation depth.

((A)) Duration water - historic rainfall ((B)) Legend



((C)) Duration water-2xNC5min ((D)) Duration water-2xNC30min ((E)) Duration water-2xNC1h

FIGURE 4.12: Results 3Di modelling - The duration of water on street.

In figure 4.12, the duration of water on street modelled by 3Di are shown. The darker the red, the longer the duration of the water is, up to 2 hours. In figure 4.12A, the results of the modelling with historic rainfall as input are shown. As there was no inundation modelled for the NC5min, NC30min and NC1h, the duration was also 0. The pattern of the duration (i.e. the intensities and locations) are similar to the inundation depths. Overall, the duration is substantially shorter with the nowcasts as input. The duration of 2 hours water on street is never reached for 2xNC5min (4.12C), 2xNC30min (4.12D) and 2xNC1h (4.12E).

4.4 Results step 4: Results statistics of effect nowcasts on projected runoff

Maximum inundation depth

Historic	19 cm
2xNC5min	17 cm = 11% less
2xNC30min	7 cm = 63% less
2xNC1h	15 cm = 21% less

TABLE 4.7: Maximum of Maximum inundation depth.

The maximum inundation depth simulated with the historic rainfall is 19 cm. This is expected to cause large nuisance. The simulation of 2xNC5min results in 17 cm and 2xNC1h results in 15 cm. These values are also expected to cause large nuisance, although less. The value of 7 cm simulated by the 2xNC30min is quite low and it is only expected to cause some inconvenience.

Duration water on street

Historic	1.20h = 1h and 12 minutes
2xNC5min	0.71h = 43 minutes = 40% shorter
2xNC30min	0.07h = 4 minutes = 94% shorter
2xNC1h	0.24h = 14 minutes = 80% shorter

TABLE 4.8: Mean Duration water on street.

The mean duration of water on street simulated with the historic rainfall is 1 hour and 12 minutes. This is expected to cause large nuisance. The simulation of 2xNC5min gives 43 minutes. This value is also expected to cause large nuisance. The values of 4 and 14 minutes simulated by the 2xNC30min and 2xNC1h respectively are quite low and are expected to cause little inconvenience.

Discussion

This thesis supports the statement of Jacks et al. (2010) that for extreme rainfall events, using nowcasts only can be a solution for quick decision making, provided that some improvements are made. The hypotheses stated at the beginning of this thesis were that nowcasts are both reliable and timely enough for this.

The historic rainfall and the NC5min resembled each other well, although there was nowcast underestimation. This is due to measurement errors of radar data (Schuurmans & De Koning, 2011) already present in the RT images. Moreover, the nowcasts perform less at high rainfall intensities, which is of course not desired. This was also found by Immerzeel (2007); Liguori and Rico-Ramirez (2012); Overeem (2010). For example, Immerzeel (2007) found that a daily sum of 40 mm has in 87% of the cases 10 mm underestimation of the radar images compared to the rain gauges. Additionally, the nowcast accuracy decreases with longer lead times, as also stated by Huang et al. (2012); Austin and Bellon (1974); Browning and Collier (1989); Lin et al. (2005). For the Netherlands as a whole, the nowcasts are considered sufficient up until 1 hour previous to the event. For smaller regions (e.g. municipalities), which need to be considered as the nowcast is highly location specific (Huang et al., 2012), and a warning system is only interesting at smaller scales, the maximum lead time is 20($\pm$10) minutes. It is highly questionable if this time is sufficient. Following from this, this thesis states that of right now, the nowcast is not provided reliably and timely enough to use for decision-makers. Therefore, according to Leskens (2015); Pidgeon and Fischhoff (2011); Projectgroep Nationale Regenradar (2013) water managers can not fully anticipate on extreme rainfall events using nowcasts alone.

A result of the 3Di simulations is that maximum inundation depths with input from nowcasts are found at the same locations as with input from historical rainfall data. However, the maximum inundation depths and the durations are lower with nowcasted input, even with a correction factor. It is very important to have the maximum and the timing of the peaks correct in order to forecast the inundation, even more so than the pattern. Large nuisance is reached in terms of inundation depth and duration for the historic rainfall and the 2xNC5min, and only in terms of inundation depth for the 2xNC1h. This means that a long lead time (e.g. 1 hour) can give almost the same level of nuisance as a short lead time (e.g. 5 minutes), which is positive news for the reliability and timeliness of the nowcasts.

This thesis rejects the second hypothesis, namely that the rainfall caused by cold fronts (e.g. 13 October 2013) is easier to forecast than convective rainfall (e.g. 28 July 2014 and 30 May 2016), though it is possible that the differences are not related to the difference in rainfall type but are solely a coincidence. The convective rainfall showed a higher correlation and a longer maximum lead time. This is explained by the method of nowcasting, where current precipitation is extrapolated in the future (Huang et al., 2012). Noud Brasjen (personal connection) explains that the extrapolation of showers used for nowcasts is easier if showers are distinctive. During the rainfall event on 13 October 2013 there was a large front. While the overall pattern of the front was quite easily distinguishable, on the smaller scale this was probably harder than in 2014 and 2016. However, the SE and BIAS of the nowcasts are not largest in 2013, probably due to the fact that the event in 2013 was less extreme in terms of local differences and peaks. The convective rainfall of 2016 was probably easier to forecast than the event of 2014, as 30 May 2016 the rainfall persisted in a large band, moving over the Netherlands from west to east, as opposed to 28 July 2014, where the showers developed and appeared quite suddenly.

Other limitations need to be addressed as well. A first, very important one, is that we only compare what we think is real. The after, finally calibrated rainfall is assumed to be the historic rainfall. 3Di is also just a simulation and not the real situation. Moreover, the BIAS, SE and COR of the nowcasts are compared with the NC5min. The NC5min is chosen to be the most reliable one in this thesis, in order to make a good judgement. Due to time constraints and insufficient knowledge of the underestimation, the BIAS could not be corrected for. Therefore, to be able to make any statement until what value a BIAS, SE or COR would be considered good enough, which was a challenging decision to make, this trade-off was made. The standard deviation used for this method was also very dependent on the time frame considered. Additionally, the COR usually has a high standard deviation. For example, a correlation of 0.70 with a standard deviation of 0.60, results in a correlation of 0.10 to be considered adequate in this study. For the maximum lead time, as three different statistics were used (BIAS, SE and COR), it was hard to determine which statistics should have more value. Therefore, it was decided to mention both the value determined by the weakest link and the average value. The last limitation to mention is the surface area of the research area. The larger the area, the more the results are averaged, and extremes are taken out. Nevertheless, this did not appear to have an effect on the statistical analysis.

In the future, if the underestimation is accounted for and the nowcasts become more accurate, I still see considerable potential for a warning system using nowcasts of extreme rainfall. However, some improvements need to be made. First of all, there should be more research in the amount of underestimation, as this thesis does not provide a clear demarcation of the amount. 1 hour prior to the event, the RT images and the NRT could be compared and a correction factor could follow from this for the new RT. Another possibility is a fast calibration with (some of) the rain gauges. Investments are needed to make this process faster. The relationship between rainfall intensities and BIAS could also be used to apply a correction of the underestimation. This needs to be done for every region or grid cell and for each lead time. Secondly, the implementation of radar images with a higher spatial resolution would increase the performance of the nowcasts, as they would make the nowcasts more accurate on the smaller scales. Finally, the nowcasts could be improved by including NWP models (e.g. HARMONIE) for longer lead times (Golding, 2000; Liguori & Rico-Ramirez, 2012; Lin et al., 2005).

A warning system can be established for urban areas, in terms of e.g. an app or an online dashboard. Local entrepreneurs and the municipality can be a part of this, and might decide to place sandbags or change routes if warnings are issued for a given area at least half an hour ahead of time. It is better to give a warning when it actually will not rain, than to be too reluctant because of your uncertainties. The threshold of when a warning is given should therefore not be too high. The threshold can also be divided by the correction factor, to account for the underestimation. The threshold should be determined from a survey specifically done for the region, for example by 3Di. This threshold should not be fixed, but it should also be dependent on the type of rainfall (e.g. convective) or other type of precipitation (e.g. hail), the hourly intensity, and the forecast for longer periods. Taken all this into account, a warning system prior to extreme rainfall would decrease the societal problem of water nuisance.

Conclusion

The main research question is how accurate rainfall nowcasts are compared to historical rainfall estimates and how hydrodynamic runoff forecasts from nowcasted rainfall differ from historical runoff simulations.

Regarding the rainfall, the performance of the nowcasts decreases for longer lead times. The maximum lead time found reliable enough is 20(±10) minutes for extreme rainfall events, depending on the event, region and statistic used. The performance also decreases for longer rainfall intensities. Lastly, the nowcasts underestimate the historic rainfall, varying from 1.3 to 3.3 times. This means that the nowcasts are only accurate for the very-short term forecasts. The underestimation is not caused by the nowcasting method, but by errors in the real time radar images. Regarding the runoff simulations, the nowcasted maximum rainfall is very important to determine the level of nuisance, both in terms of maximum inundation depths and the duration. Also the timing is important. Additionally, a higher lead time did not necessarily mean a forecast of less nuisance.

The first sub question is if nowcasts need improvements and if there is a potential for nowcasts to be used as some kind of warning system. An improvement needed is a correction for the underestimation. A correction factor of 2 seems a good estimate. The maximum lead time to be considered adequate might be too short for now in some cases. However, the difference seems irrelevant concerning the maximum inundation depths and duration if the correction factor is used. The second sub question is if there is a difference in the performance of nowcasts during different types of precipitation. There is no pattern found in the type of rainfall, but there are differences.

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Appendix 1: Interview

Datum: 15-3-2016
Contactpersoon: Noud Brasjen
Naam organisatie: Infoplaza
Functie: Analist weersverwachtingen

1. Bij welke typen neerslag is nowcast het meest betrouwbaar en bij welke juist niet? (denk aan: convectie, warmte en koude fronten, onweersbuien)

Grootschalige buien zijn het makkelijkst en meest nauwkeurig te voorspellen, mits ze niet zo groot zijn dat ze het hele radarbeeld bedekken, zodat je niet weet waar de bui vandaan komt. Bij convectieve of onweersbuien is de (trek)richting goed te voorspellen, maar het ontstaan en de intensiteit van de buien niet goed. Het meest ideaal om verwachtingen mee te maken zijn koudefronten. Deze hebben een lange lijn met grote intensiteit die je makkelijk kan doortrekken. Het verschil tussen een koudefront en een warmtefront is niet altijd makkelijk te onderscheiden.

2. Hoe worden de nowcastbeelden verwerkt? Alleen gextrapoleerd of worden er ook andere bewerkingen toegepast?

Bij Infoplaza krijgen ze radarbeelden die ze omrekenen naar neerslag. De huidige neerslag wordt doorgetrokken in de richting afgeleid van het afgelopen uur. De trekrichtingen worden als volgt berekend:

1. Een ruisfilter wordt gebruikt om de radarbeelden van het KNMI te ontdoen van valse reflecties.
2. De twee meest recente radarbeelden worden in blokken opgedeeld, waarbij de verschuiving van ieder blok wordt bepaald door te zoeken naar de maximum kruiscorrelatie.

3. Het overgebleven vectorveld wordt gefilterd met behulp van de verkregen kruiscorrelaties.
4. Als laatste stap wordt de divergentie-component van het vectorveld weggefilterd met behulp van vectorveld decompositie.

Bij de nowcastbeelden wordt geen ontwikkeling van buien meegenomen en geen windrichting. Daarvoor heb je weermodellen nodig, die dan weer langer nodig hebben om te rekenen. Wel wordt uitdoving meegenomen, ook door de trend van het afgelopen uur door te rekenen.

3. Tot welke lead time is nowcast betrouwbaar?
De meningen zijn verdeeld over tot welke lead time nowcast betrouwbaar is. Noud Brasjen haalde zelf uit de literatuur tot 2 uur, en wist dat met zijn studie op te rekken naar 2,5 uur. Hij vergelijkt hiervoor zijn gegevens met het KNMI.

4. Denk je dat door klimaatverandering de rol van nowcast verandert?
Klimaatverandering zal de rol van nowcast veranderen door het verschil in extreme buien, maar pas over een langere tijd. Waarschijnlijker is dat de ontwikkelingen in nowcast, o.a. door betere modellen, meer invloed hebben.

5. Welke verbeteringen zijn er nodig aan nowcasting? Wat is er mogelijk op de korte termijn? Wanneer is nowcast goed genoeg?
Een verbetering aan nowcast kan zijn om de verticale ontwikkeling van buien mee te nemen. Hiervoor is momenteel nog geen oplossing, maar mogelijk is er in de toekomst meer computerkracht, waardoor de modellen in plaats van elke paar uur elk kwartier een verwachting kunnen geven. Er blijft hierbij altijd een vertraging, maar die hebben we het liefst zo kort mogelijk. Dit kan bijvoorbeeld ook bereikt worden door kleinschalige modellen. De ontwikkeling van buien blijft lastig, zeker met convectieve onweersbuien. Eventueel kunnen wolken ook gebruikt worden voor het bepalen van de trekrichting.

Appendix 2: Locations

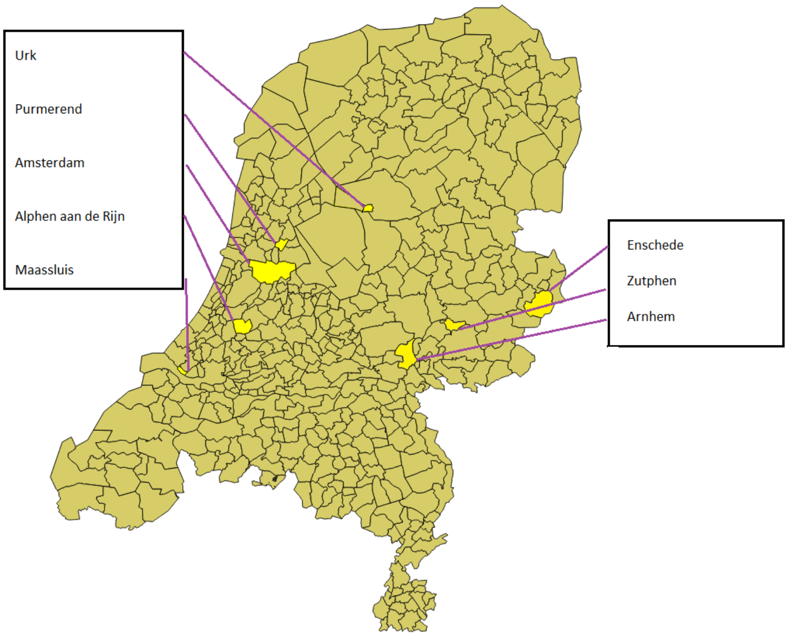


FIGURE 4.13: The Netherlands. The regions used for the analysis are displayed in yellow.

Rainfall intensity per region

Region	Start time and date	Maximum hourly rainfall sum
Amsterdam	13-10-13, 11h25	7 mm
Maassluis	13-10-13, 09h40	10 mm
Purmerend	13-10-13, 11h45	9 mm
Alphen aan de Rijn	28-07-14, 09h05	25 mm
Amsterdam	28-07-14, 9h40	22 mm
Urk	28-07-14, 03h00	25 mm
Arnhem	30-05-2016, 17h20	23 mm
Enschede	30-05-2016, 18h30	18 mm
Zutphen	30-05-2016, 17h20	29 mm

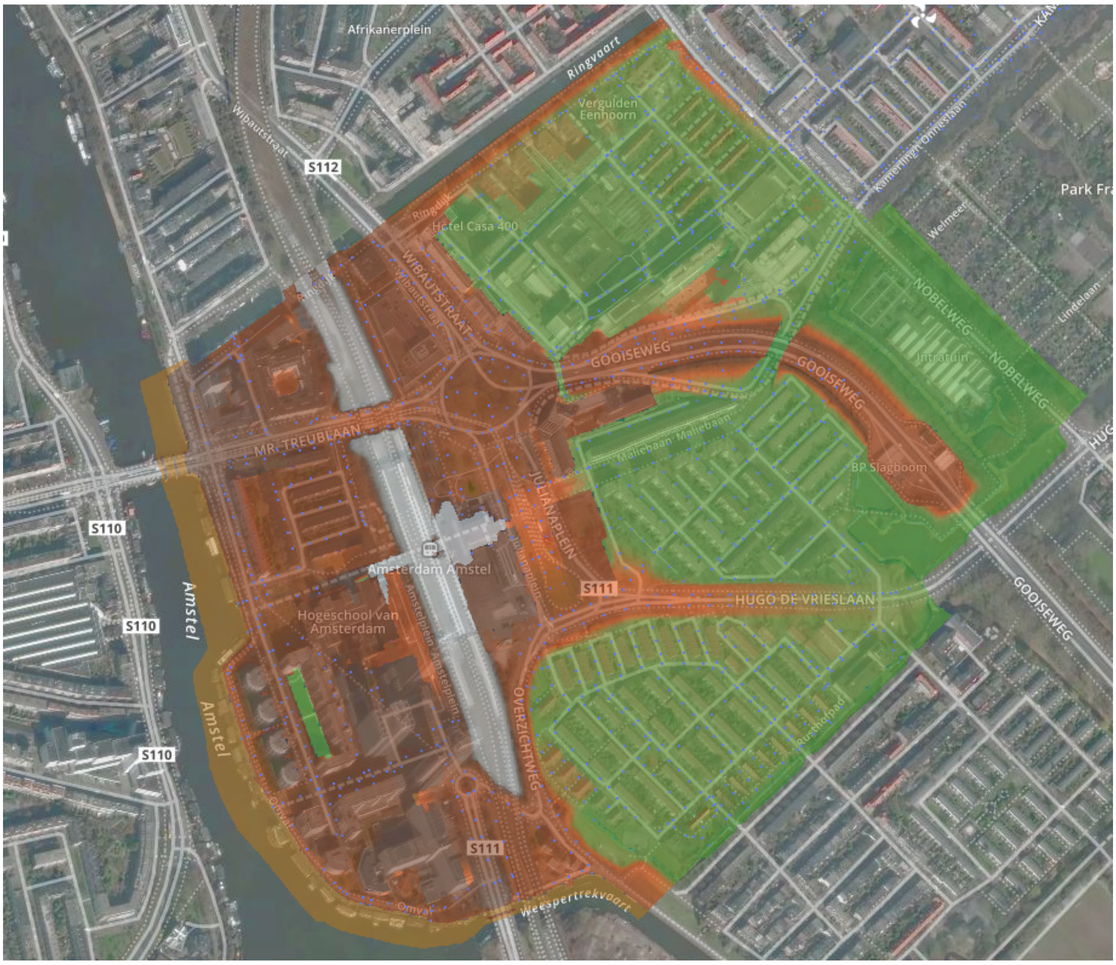


Figure 4.14: The area used in the 3Di modelling. The area is a part of Amsterdam, centered around the trainstation Amsterdam Amstel. The DEM is shown in red and green.

Appendix 3: Scripts

In this appendix some important (part of the) scripts can found. Only the part of the nowcast with 5 minute lead is shown. The other lead times are likewise.

BIAS

$< performanceIndicatorSet >$

$< inputVariablevariableId = ”after” >$

$< timeSeriesSet >$

...

$< /timeSeriesSet >$

$< /inputVariable >$

$< inputVariablevariableId = ”NC2” >$

$< timeSeriesSet >$

$\ldots$

$< /timeSeriesSet >$

$< /inputVariable >$

$< modulePerformanceIndicatorobservedVariableId = ”after” calculatedVariableId =$
$”NC2” outputVariableId = ”outputbiasNC2”$
$indicatorType = ”bias” >$

$< /modulePerformanceIndicator >$

$< outputVariablevariableId = ”outputbiasNC2” >$

$< timeSeriesSet >$

...

$< /timeSeriesSet >$

$< /outputVariable >$

$< /performanceIndicatorSet >$

The COR was likewise, all 'bias' entries should then be 'cor', and $indicatorType =$ $''CorrelationCoeffient'' >$. The same goes for the calculated RMSE, needed for the SE.

SE

$< transformationid = ''SDE - 5m'' >$

$< user >$

$< simple >$

$< inputVariableDefinition >$

$< variableId > outputRMSENC2 < /variableId >$

$< timeSeriesSet >$

...

$< /timeSeriesSet >$

$< /inputVariableDefinition >$

$< inputVariableDefinition >$

$< variableId > outputbiasNC2 < /variableId >$

$< timeSeriesSet >$

...

$< /timeSeriesSet >$

$< /inputVariableDefinition >$

$< expression > sqrt((outputRMSENC2)^2 - (outputbiasNC2)^2) < /expression >$

$< outputVariable >$

$< timeSeriesSet >$

...

$< /timeSeriesSet >$

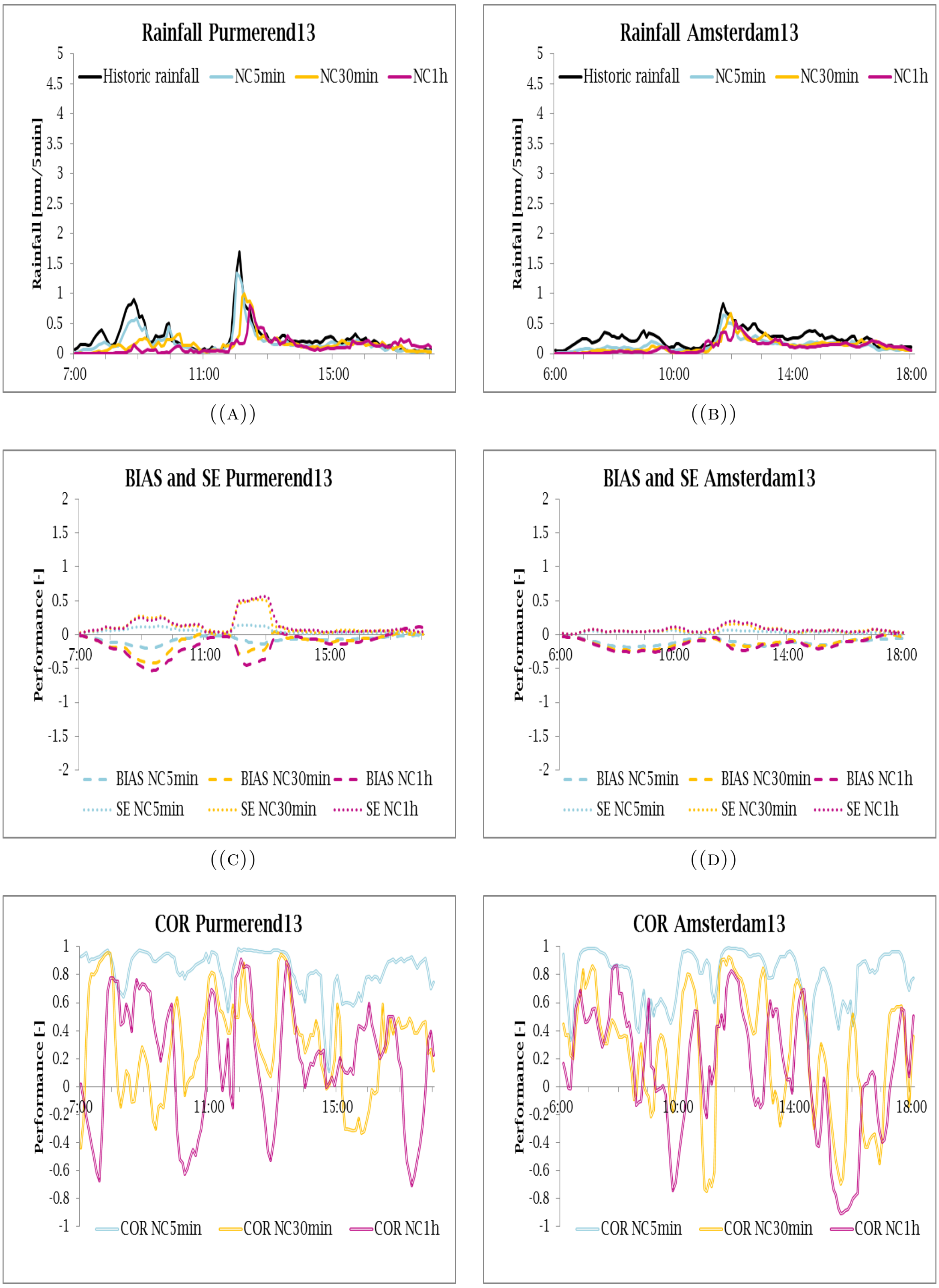
$< /outputVariable >$

$< /simple >$

$< /user >$

$< /transformation >$

Appendix 4: Graphs

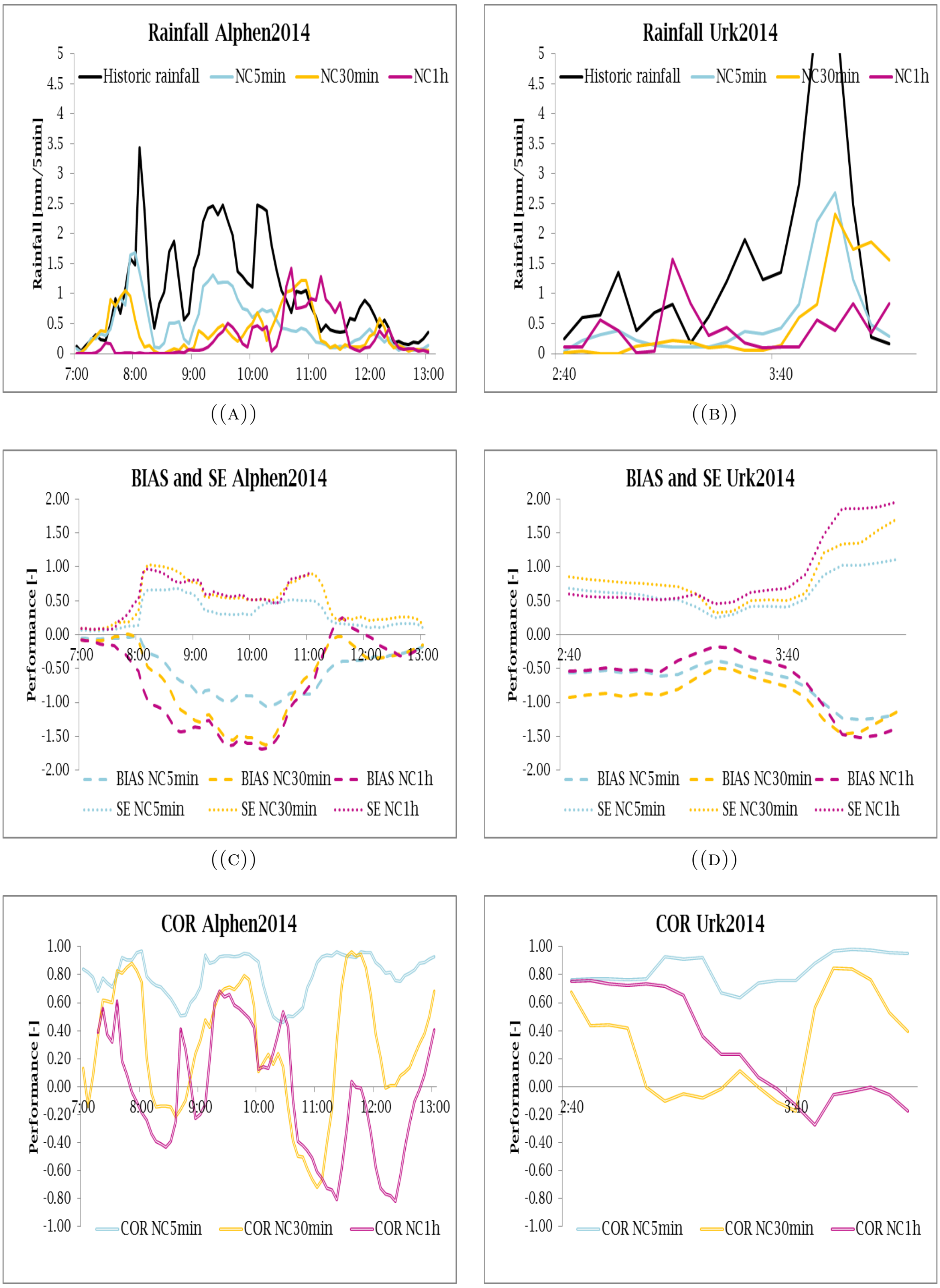


((A)) ((B))

((C)) ((D))

((E)) ((F))

FIGURE 4.15: The historic rainfall, nowcasted rainfall, BIAS, SE and COR averaged over Purmerend and Amsterdam on 13 October 2013.

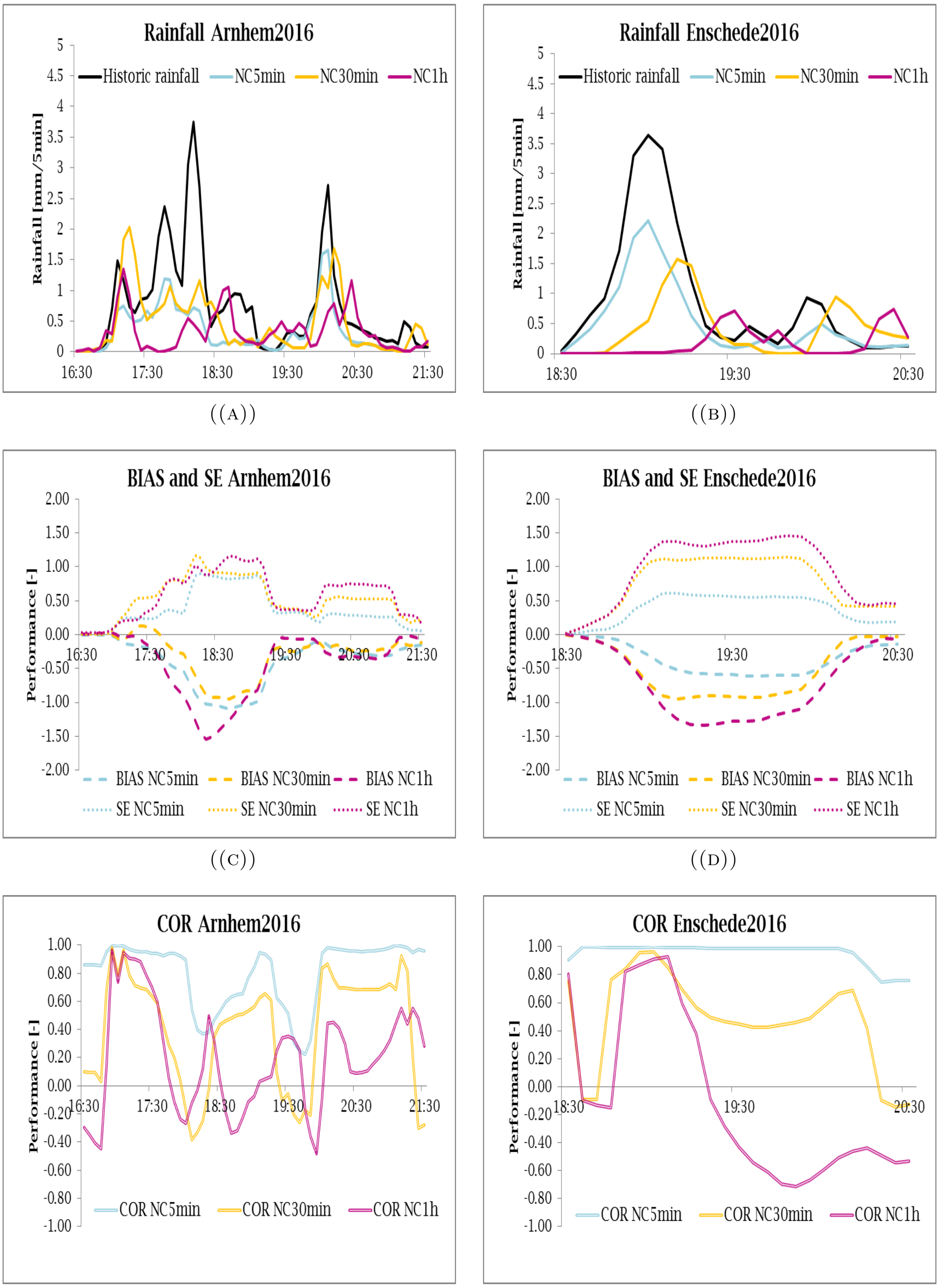


((A)) ((B))

((C)) ((D))

((E)) ((F))

FIGURE 4.16: The historic rainfall, nowcasted rainfall, BIAS, SE and COR averaged over Alphen aan de Rijn and Urk on 28 July 2014.



((A)) ((B))

((C)) ((D))

((E)) ((F))

FIGURE 4.17: The historic rainfall, nowcasted rainfall, BIAS, SE and COR averaged over Arnhem and Enschede on 30 May 2016.

Appendix 5: Performance nowcast per rainfall intensity

Maximum hourly rainfall sum	mean BIAS	mean SE	mean COR
7	-0.10	0.07	0.97
9	-0.08	0.11	0.96
10	-0.28	0.25	0.71
18	-0.30	0.37	0.99
22	-0.62	0.28	0.63
23	-0.51	0.45	0.78
25	-0.91	0.33	0.91
25	-0.70	0.56	0.84
29	-0.94	0.76	0.93

Maximum hourly rainfall sum (mm/hour)	mean BIAS	mean SE	mean COR
5-10	-0.09	0.09	0.97
10-15	-0.28	0.25	0.71
15-20	-0.30	0.37	0.99
20-25	-0.56	0.37	0.71
25-30	-0.85	0.55	0.89
Trend	Increases	Increases	No trend

Table 4.9: Performance nowcast per rainfall intensity.

Appendix 6: Calculation maximum lead time

Netherlands (20-18h) 2013

BIAS: min=-0.093 ; sd=0.017 ; min-sd=-0.110 → minimum BIAS should be $>$ -0.110

SE: max=0.141 ; sd=0.003 ; max+sd=0.017 → maximum SE should be $<$ 0.017

COR: mean=0.523 ; sd=0.447 ; mean-sd=0.073 → mean COR should be $>$ 0.073

Historic rainfall and:	BIAS	SE	COR
nowcast 5 min lead	-0.093	0.014	0.447
nowcast 10 min lead	-0.094	0.015	0.441
nowcast 15 min lead	-0.094	0.016	0.397
nowcast 20 min lead	-0.095	0.016	0.338
nowcast 25 min lead	-0.097	0.017	0.280
nowcast 30 min lead	-0.098	0.017	0.209
nowcast 35 min lead	-0.100	0.018	0.151
nowcast 40 min lead	-0.101	0.018	0.164
nowcast 45 min lead	-0.101	0.018	0.141
nowcast 1 hour lead	-0.104	0.019	0.224

TABLE 4.10: Calculation maximum lead time Netherlands 20h00 12 October -18h00 13 October 2013.

*A correlation of 0.073 is barely any correlation.

Maassluis (21-18h) 2013

BIAS: min=-1.3 ; sd=0.26 ; min-sd=-1.56 → minimum BIAS should be > -1.56

SE: max=0.667 ; sd=0.134 ; max+sd=0.801 → maximum SE should be < 0.801

COR: mean=0.713 ; sd=0.278 ; mean-sd=0.435 → mean COR should be > 0.435

Historic rainfall and:	BIAS	SE	COR
nowcast 5 min lead	-1.300	0.667	0.713
nowcast 10 min lead	-1.341	0.821	0.512
nowcast 15 min lead	-1.351	0.845	0.436
nowcast 20 min lead	-1.310	0.726	0.395
nowcast 25 min lead	-1.221	0.658	0.377
nowcast 30 min lead	-1.137	0.604	0.312

TABLE 4.11: Calculation maximum lead time Maassluis 21h00 12 October - 18h00 13 October 2013.

Note: For Maassluis in 2013, the trend of BIAS and SE is not declining for longer lead times, which is unexpected.

Amsterdam (6-18h) 2013

BIAS: min=-0.191 ; sd=0.045 ; min-sd=-0.236 → minimum BIAS should be > -0.236

SE: max=0.068 ; sd=0.015 ; max+sd=0.083 → maximum SE should be < 0.083

COR: mean=0.793 ; sd=0.183 ; mean-sd=0.610 → mean COR should be > 0.610

Historic rainfall and:	BIAS	SE	COR
nowcast 5 min lead	-0.191	0.068	0.793
nowcast 10 min lead	-0.206	0.087	0.645
nowcast 15 min lead	-0.218	0.107	0.473
nowcast 20 min lead	-0.228	0.131	0.300
nowcast 25 min lead	-0.235	0.142	0.237
nowcast 30 min lead	-0.239	0.158	0.244

TABLE 4.12: Calculation maximum lead time Amsterdam 6h00-18h00 13 October 2013.

Purmerend (7-18h) 2013

BIAS: min=-0.203 ; sd=0.049 ; min-sd=-0.252 → minimum BIAS should be > -0.252

SE: max=0.141 ; sd=0.039 ; max+sd=0.180 → maximum SE should be < 0.180

COR: mean=0.836 ; sd=0.149 ; mean-sd=0.687 → mean COR should be > 0.687

Historic rainfall and:	BIAS	SE	COR
nowcast 5 min lead	-0.203	0.141	0.836
nowcast 10 min lead	-0.258	0.210	0.615
nowcast 15 min lead	-0.307	0.285	0.449
nowcast 20 min lead	-0.352	0.369	0.341
nowcast 25 min lead	-0.392	0.457	0.293
nowcast 30 min lead	-0.421	0.518	0.293

TABLE 4.13: Calculation maximum lead time Purmerend 7h00-18h00 13 October 2013.

Netherlands (2-16h) 2014

BIAS: min=-0.118 ; sd=0.036 ; min-sd=-0.154 → minimum BIAS should be > -0.154

SE: max=0.05 ; sd=0.01 ; max+sd=0.06 → maximum SE should be < 0.06

COR: mean=0.5707 ; sd=0.402 ; mean-sd=0.1687 → mean COR should be > 0.1687

Historic rainfall and:	BIAS	SE	COR
nowcast 5 min lead	-0.118	0.050	0.5707
nowcast 10 min lead	-0.119	0.050	0.552
nowcast 15 min lead	-0.120	0.050	0.525
nowcast 20 min lead	-0.121	0.050	0.449
nowcast 25 min lead	-0.122	0.051	0.461
nowcast 30 min lead	-0.124	0.051	0.430
nowcast 45 min lead	-0.132	0.051	0.371
nowcast 1 hour lead	-0.139	0.052	0.360

TABLE 4.14: Calculation maximum lead time Netherlands 2h00 - 16h00 28 July 2014.

Alphen (7-13h30) 2014

BIAS: min=-1.063 ; sd=0.342 ; min-sd=-1.405 → minimum BIAS should be > -1.405

SE: max=0.687 ; sd=0.201 ; max+sd=0.888 → maximum SE should be < 0.888

COR: mean=0.804 ; sd=0.201 ; mean-sd=0.657 → mean COR should be > 0.657

Historic rainfall and:	BIAS	SE	COR
nowcast 5 min lead	-1.063	0.687	0.804
nowcast 10 min lead	-1.163	0.722	0.662
nowcast 15 min lead	-1.263	0.711	0.507
nowcast 20 min lead	-1.401	0.831	0.353
nowcast 25 min lead	-1.533	0.994	0.266
nowcast 30 min lead	-1.625	1.03	0.277

Table 4.15: Calculation maximum lead time Alphen aan de Rijn 7h00-13h30 28 July 2014.

Amsterdam (8-12h) 2014

BIAS: min=-1.003 ; sd=0.309 ; min-sd=-1.312 → minimum BIAS should be > -1.302

SE: max=0.367 ; sd=0.09 ; max+sd=0.457 → maximum SE should be < 0.457

COR: mean=0.797 ; sd=0.264 ; mean-sd=0.533 → mean COR should be > 0.533

Historic rainfall and:	BIAS	SE	COR
nowcast 5 min lead	-1.003	0.367	0.797
nowcast 10 min lead	-1.102	0.423	0.739
nowcast 15 min lead	-1.22	0.486	0.678
nowcast 20 min lead	-1.315	0.526	0.606
nowcast 25 min lead	-1.373	0.559	0.539
nowcast 30 min lead	-1.439	0.617	0.416

Table 4.16: Calculation maximum lead time Amsterdam 8h00-12h00 28 July 2014.

Urk (2h40-4h) 2014

BIAS: min=-1.256 ; sd=0.288 ; min-sd=-1.544 → minimum BIAS should be $>$ -1.544

SE: max=1.06 ; sd=0.247 ; max+sd=1.307 → maximum SE should be $<$ 1.307

COR: mean=0.829 ; sd=0.111 ; mean-sd=0.718 → mean COR should be $>$ 0.718

Historic rainfall and:	BIAS	SE	COR
nowcast 5 min lead	-1.256	1.06	0.829
nowcast 10 min lead	-1.236	1.16	0.752
nowcast 15 min lead	-1.282	1.359	0.404
nowcast 20 min lead	-1.315	1.37	0.246
nowcast 25 min lead	-1.385	1.558	0.134
nowcast 30 min lead	-1.478	1.547	0.238

TABLE 4.17: Calculation maximum lead time Urk 2h40-4h00 28 July 2014.

Netherlands (16h-21h) 2016

BIAS: min=-0.093 ; sd=0.026 ; min-sd=-0.119 → minimum BIAS should be $>$ -0.119

SE: max=0.024 ; sd=0.006 ; max+sd=0.03 → maximum SE should be $<$ 0.03

COR: mean=0.582 ; sd=0.506 ; mean-sd=0.076 → mean COR should be $>$ 0.076*

Historic rainfall and:	BIAS	SE	COR
nowcast 5 min lead	-0.093	0.024	0.582
nowcast 10 min lead	-0.093	0.023	0.552
nowcast 15 min lead	-0.092	0.023	0.536
nowcast 20 min lead	-0.092	0.024	0.500
nowcast 25 min lead	-0.091	0.024	0.459
nowcast 30 min lead	-0.093	0.024	0.421
nowcast 35 min lead	-0.098	0.028	0.366
nowcast 40 min lead	-0.103	0.031	0.289
nowcast 45 min lead	-0.110	0.034	0.245
nowcast 50 min lead	-0.116	0.037	0.239
nowcast 55 min lead	-0.122	0.042	0.246
nowcast 1 hour lead	-0.128	0.046	0.273

TABLE 4.18: Calculation maximum lead time Netherlands 16h00 - 21h00 30 May 2016.

*A correlation of 0.076 is barely any correlation.

Arnhem (16h50-21h30) 2016

BIAS: min=-1.098 ; sd=0.344 ; min-sd=-1.442 → minimum BIAS should be > -1.442

SE: max=0.900 ; sd=0.269 ; max+sd=1.169 → maximum SE should be < 1.169

COR: mean=0.802 ; sd=0.236 ; mean-sd=0.566 → mean COR should be > 0.566

Historic rainfall and:	BIAS	SE	COR
nowcast 5 min lead	-1.098	0.900	0.802
nowcast 10 min lead	-1.043	0.936	0.742
nowcast 15 min lead	-1.024	0.983	0.655
nowcast 20 min lead	-1.021	1.007	0.566
nowcast 25 min lead	-0.986	1.074	0.514
nowcast 30 min lead	-0.949	1.172	0.420
nowcast 35 min lead	-0.954		
nowcast 40 min lead	-1.025		
nowcast 45 min lead	-1.171		
nowcast 50 min lead	-1.29		
nowcast 55 min lead	-1.444		
nowcast 1 hour lead	-1.54		

TABLE 4.19: Calculation maximum lead time Arnhem 16h50-21h30 30 May 2016.

Note: For Arnhem in 2016, the BIAS is becoming smaller for longer lead times, which is unexpected.

Enschede (18h30-20h) 2016

BIAS: min=-0.615 ; sd=0.245 ; min-sd=-0.860 → minimum BIAS should be > -0.860

SE: max=0.609 ; sd=0.222 ; max+sd=0.831 → maximum SE should be < 0.831

COR: mean=0.988 ; sd=0.020 ; mean-sd=0.968 → mean COR should be > 0.968

Historic rainfall and:	BIAS	SE	COR
nowcast 5 min lead	0.615	0.609	0.988
nowcast 10 min lead	-0.620	0.622	0.977
nowcast 15 min lead	-0.615	0.636	0.965
nowcast 20 min lead	-0.671	0.730	0.918
nowcast 25 min lead	-0.806	0.955	0.784
nowcast 30 min lead	-0.948	1.141	0.584

TABLE 4.20: Calculation maximum lead time Enschede 18h30-20h00 30 May 2016.

Zutphen (16h-21h) 2016

BIAS: min=-1.367 ; sd=0.409 ; min-sd=-1.776 → minimum BIAS should be $>$ -1.776

SE: max=1.101 ; sd=0.321 ; max+sd=1.422 → maximum SE should be $<$ 1.422

COR: mean=0.940 ; sd=0.059 ; mean-sd=0.881 → mean COR should be $>$ 0.881

Historic rainfall and:	BIAS	SE	COR
nowcast 5 min lead	-1.367	1.101	0.940
nowcast 10 min lead	-1.469	1.232	0.860
nowcast 15 min lead	-1.532	1.334	0.781
nowcast 20 min lead	-1.539	1.399	0.655
nowcast 25 min lead	-1.553	1.441	0.522
nowcast 30 min lead	-1.566	1.509	0.398
nowcast 35 min lead	-1.629		
nowcast 40 min lead	-1.648		
nowcast 45 min lead	-1.696		
nowcast 50 min lead	-1.776		
nowcast 55 min lead	-1.895		
nowcast 1 hour lead	-1.970		

Table 4.21: Calculation maximum lead time Zutphen 16h00-21h00 30 May 2016.

The mean value of the statistics averaged over the regions and events is (20+5+10+22+13+15+42+22+12)/9 = 18 minutes. The minimum value averaged over the regions and events is (5+13+12)/3= 10 minutes. The maximum value averaged over the regions and events is (20+22+42)/3= 28 minutes.

Appendix 7: Inundation depths for different time steps

FIGURE 4.18: Inundation depths at t=197 minutes after start event (maximum levels).

FIGURE 4.19: Inundation depths at t=157 minutes after start event (maximum levels).

Figure 4.20: Inundation depths at t=135 minutes after start event (maximum levels).

Figure 4.21: Inundation depths at t=90 minutes after start event (maximum levels).

Appendix 8: Statistics effect historic rainfall and nowcasted rainfall on projected runoff

Because the number of points (N) should be the same if we compare the mean, the maximum number of points (29 by the historic rainfall) is used for all cases. If N is smaller than 29, the mean should be calculated manually. If there is no point displayed, this means that the inundation height is 0. (29-N)*0 is added to the sum and then the sum is divided by 29, or basically, the sum is divided by 29.

Maximum inundation depth

Max	19 cm
N	29
Mean	9 cm

Table 4.22: Statistics historic rainfall

Max	17 cm
N	20
Sum	((29-20)*0 +1.49725127184)
Mean	((29-20)*0 +1.49725127184)/29 = 5 cm

Table 4.23: Statistics 2xNC5min

Max	7 cm
N	3
Sum	((29-3)*0 +0.18929284982)
Mean	((29-3)*0 +0.18929284982)/29 = 1 cm

Table 4.24: Statistics 2xNC30min

Max	15 cm
N	17
Sum	((29-17)*0 +1.13886858732)
Mean	((29-17)*0 +1.13886858732)/29 = 4 cm

Table 4.25: Statistics 2xNC1h

Historic	9 cm
2xNC5min	5 cm
2xNC30min	1 cm
2xNC1h	4 cm

Table 4.26: Mean of Maximum inundation depth.

Duration water on street

Max	2.07 h = 2h and 4 minutes
N	29
Mean	1.20h = 1h and 12 minutes

Table 4.27: Statistics historic rainfall

Max	1.77h =1h and 46 minutes
N	20
Sum	((29-20)*0 +20.686)
Mean	((29-20)*0 +20.686)/29 = 0.71h = 43 minutes

Table 4.28: Statistics 2xNC5min

Max	0.75h = 45 minutes
N	3
Sum	((29-3)*0 +2.15020315341)
Mean	((29-3)*0 +2.15020315341)/29 = 0.07h = 4 minutes

Table 4.29: Statistics 2xNC30min

Max	1.18h=1h and 11 minutes
N	17
Sum	((29-17)*0 +6.98403057938)
Mean	((29-17)*0 +6.98403057938)/29 = 0.24h = 14 minutes

Table 4.30: Statistics 2xNC1h

Historic	2.07 h = 2h and 4 minutes
2xNC5min	1.77h =1h and 46 minutes
2xNC30min	0.75h = 45 minutes
2xNC1h	1.18h=1h and 11 minutes

Table 4.31: Maximum Duration water on street.