Gauge measurements and ground-radar observations of rainfall over the Water Board district Regge and Dinkel

TERENCE DARLINGTON MUSHORE
February, 2012

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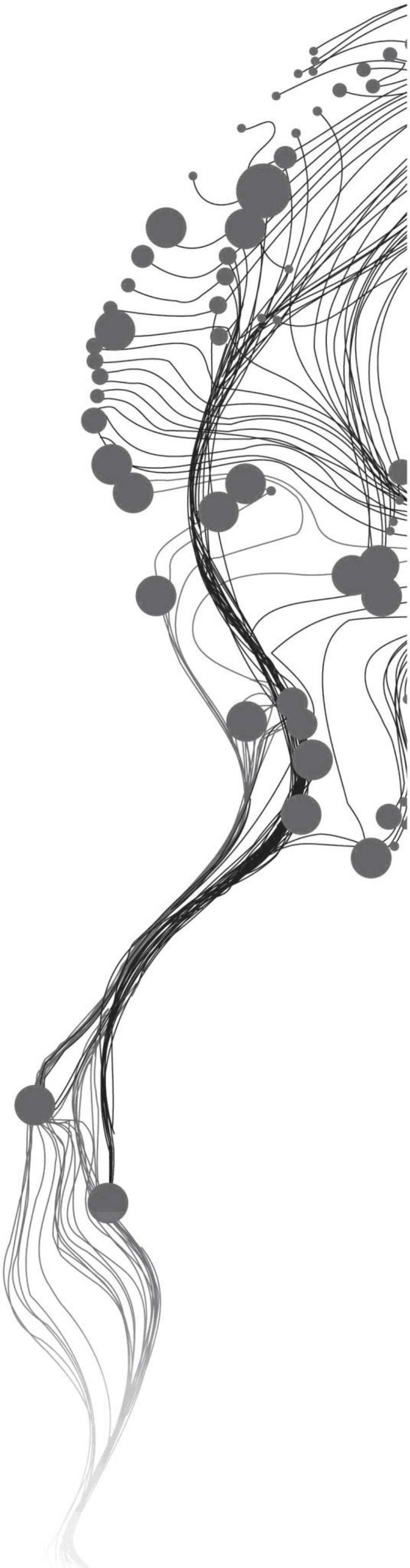

Gauge measurements and ground-radar observations of rainfall over the Water Board district Regge and Dinkel

TERENCE DARLINGTON MUSHORE
Enschede, The Netherlands, March, 2012

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Water Resources and Environmental Management

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ABSTRACT

Analysis of in situ measurements showed that the average annual rainfall for locations within the Regge and Dinkel district was in the range 700 to 900 mm for the period between 2006 and 2010. There was a slight increase in rainfall amounts as we move north eastwards across the Regge and Dinkel district. The month of April was found to be relatively drier than the other months while the area received rainfall in all months of the year. July to September coincided with the wettest parts of the year on average.

The relationships between radar reflectivity (*Z*) and rain-rate (*R*) adjusted to the climatology Regge and Dinkel district were established using the window probability matching method. A kernel of 3 by 3 pixels was used to spatially average radar reflectivity values coinciding with each of the 9 rain-gauges for a time step of one hour. The relationships were established for a time independent (bulk) calibration, for the seasonal calibration as well as for each of the years from 2006 to 2010 separately. The *Z*-*R* relationships obtained in each of the calibrations were compared with the Marshall and Palmer *Z*-*R* relationship which is currently being used over the Netherlands by the Royal Netherlands Meteorological Institute (KNMI).

The reflectivity-rain-rate relationships were found to vary from time to time over the period considered since different relationships were obtained for each calibration. In agreement with other previous works, the *Z*-*R* relationship obtained for a particular calibration was found to be dependent on the threshold for minimum reflectivity used to correspond with minimum measurable rain-rate. The *Z*-*R* relationships obtained were unique, though in the same range with others found in literature and very different from the Marshall and Palmer *Z*-*R* relationship. This implies that it is important to uniquely define the *Z*-*R* relationship for a given region since it is not the same everywhere. The variations are due to difference in drop size distribution and hence predominant rainfall types in space and time.

However, the *Z*-*R* relationships obtained using the window probability matching did not improve the accuracy of point and aerial radar rainfall estimation. The root mean square errors and mean absolute errors were higher using the proposed *Z*-*R* relationships than when using the Marshall and Palmer *Z*-*R* relationship. There is still need to adjust the method in order to further increase the accuracy. Techniques to improve accuracy were recommended which include assessment of and correction for the effect of radar range degradation as well as application of other data assimilation techniques to improve rainfall estimation over the Regge and Dinkel. Although, due to effects of range the accuracy of the radar rainfall estimates could not improve over the Regge and Dinkel after calibration it was still recommended that calibration should be done for locations in the Netherlands located within appropriate ranges from the radar. Based on previous studies, the method could be of benefit in such areas of the Netherlands.

ACKNOWLEDGEMENTS

I would like to express heartfelt thanks to my supervisors Dr. Ir. R. Van der Velde and Dr. Ir. Mhd. S. Salama for their support, dedicated guidance and encouragement throughout the thesis period. They kept me standing and pushing on by guiding my progress and motivating me to work hard throughout the research period and even before that. On a similar note I am proud and grateful of all the members of staff at ITC most particularly the Water Resources Department staff. Referring to the tools and techniques you instilled in us allowed us to handle each scientific problem in various ways. We always had many ways of solving each problem because you really filled us with Science.

I would also like to thank staff members of the Water Board Regge particularly Mr. Sjon Moninx and Mr. Henk Top for generously providing me with in-situ rainfall data. Similarly so, I would like to thank Klaas Jan van Heeringen Deltares and Hidde Leijnse from KNMI for provision of radar reflectivity data and information related to it. I trully and fully appreciate their quick responses, generosity and support.

I would also like to thank the Government of the Netherlands through NUFFIC for offering me a scholarship to pursue quality studies at ITC. I never faced challenges because their support was sufficient to keep me going and made studies manageable and interesting.

All the members of my family including in-laws were the source of inspiration to me. They always gave me strength each time I felt too tired by the confidence they had in me. My father, Terence Mushore Senior, and my mother, Cathrine, were always with adequate words to strengthen me. You always found ways of checking on me and that made me feel close to home though physically very far from it. My brother, Washington, always tried to understand whatever I was studying in attempt to feel the same pain with me. The other members which are Pauline, Pamela, Moreblessing, Tsitsi, Tendai and Wellington Mushore and Paradzai Mavhungaalways had a way of supporting me which made me confident throughout my studies.

I would also like to thank all my friends most specifically Tirivanhu Muhwati, the Magweregwedes, Mr. Nyanyiwa, young Chikwino couple, Farai Marumbwa, Juliet Gwenzi, Plaxcedes Ruzvidzo, Timothy Dube, Mary Chawira, Abel Chemura, Christabel Maguma, Faith Mashonga, Tsitsi Muparari and Tsitsi Bangira for encouraging me to keep on keeping on. My international friends made Enschede to become a home away from home. The unity of the Zimbabwean family at ITC was a very close mimic of our home set up. I would like to acknowledge Pastor Maraura in a similar way as all my other spiritual relatives.

I would also like to acknowledge the Government of Zimbabwe through the Meteorological Services Department of Zimbabwe for granting me the study leave as well as continued support throughout my study period. I would like to specifically mention the Director of the Meteorological Services, Dr. A. Makarau for his words of encouragement and many other favours which kept me pushing on.

I would not like to conclude without mentioning the inspiration which I got from the ITC-CF Church. Praising and worshipping was the best refresher I ever had in life before. I give all the glory to the Almighty God for the success He granted me.

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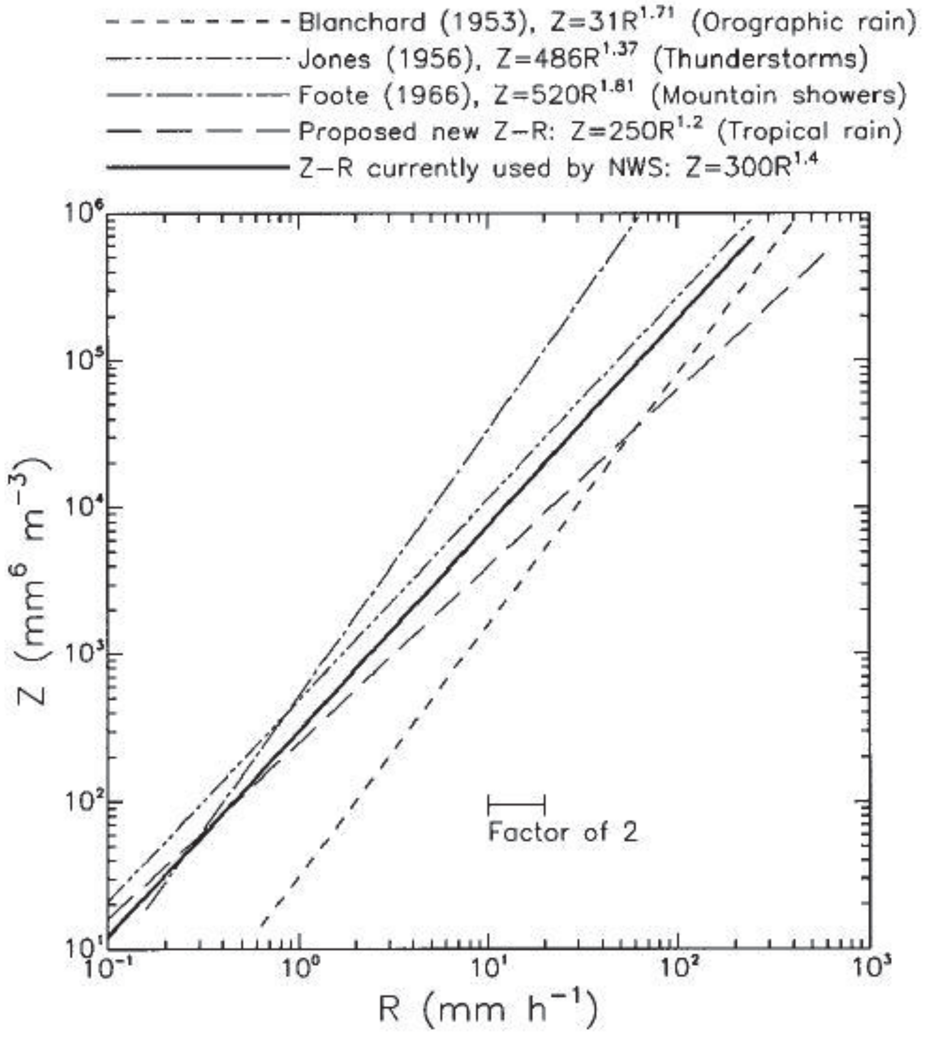
1. INTRODUCTION

1.1. Problem definition

Rainfall data are used as input for hydro-meteorological models, decision support systems, and agricultural monitoring systems. The accuracy of these applications is strongly affected by the reliability of the rainfall data used (Borga, 2002; Krajewski & Smith, 2002; G. Villarini, & Krajewski W. F., 2010). Rainfall is conventionally measured using rain gauges and these are viewed as reference for assessing the accuracy of other techniques. Gauges, however, sample rainfall at individual points and their management is expensive (Borga, 2002). Many gauges are needed to adequately detect rainfall over a large area which is costly and does not provide a complete coverage of rainfall distributions. Alternatively, rainfall can also be measured using optical and microwave remote sensing techniques. In this way electromagnetic radiation is used to detect cloud/water properties, which are then converted to rain rates.

Remote sensing usually produces data with higher space-time resolution than rain gauges. However, space-time resolution should not increase at the expense of accuracy of the data. At coincident points/pixels, rainfall measured by remote sensing should be very close in value to that measured by corresponding rain gauges (Barnston & Thomas, 1983; Biggs & Atkinson, 2011; Borga, 2002). The systematic difference between the values is called bias and contributes to uncertainty (Biggs & Atkinson, 2011). This can be caused by systematic errors of the remote sensing instrument or inadequate way of changing from radiation properties sensed to rainfall. Calibration of remote sensing products against rain gauge measurements is, therefore, needed to minimize these errors.

Ground weather radar is an example of a remote sensing instrument used to measure rainfall amount and this study will look at these radars with the main purpose of reducing bias in radar rainfall estimates in the Regge and Dinkel district of Netherlands. The ground weather radar is an active sensor that sends and receives microwave radiation and calculates the ratio of the received to the sent to come up with a reflectivity factor (*Z*) (Wilson & Brandes, 1979). Many points are sampled and a high resolution radar reflectivity map is produced. Reflectivity values measured are then converted to rain rates by an empirical algorithm and eventually to rainfall amounts.



Source (Ulbrich, 1999)

Figure 1: *Z-R* relationships (example) for different rainfall types

The reflectivity is a function of drop size distribution (usually fourth or sixth power) (Holleman, 2006; Wilson & Brandes, 1979). The relationship between radar reflectivity and rain rate (*Z-R* relationship) is not the same everywhere and has high variability (Alfieri *et al.*, 2010; Holleman, 2006; Shelton, 2009; Strangeways, 2007; G. Villarini, & Krajewski, W. F.,, 2009; Wilson & Brandes, 1979). It differs with rainfall types (cumuliform or stratiform) (see example in Figure 1) and with climatology but operationally averaged relationships used. There are many possible *Z-R* relationships, but each place has its own due to climatology and dominant rainfall types such that using one relationship in all areas (e.g. whole country) can be a source of error. Different *Z-R* relationships used in hydrometeorology imply different properties of resulting radar rainfall products (Ciach & Krajewski, 1999).

The major sources of error in ground radar rainfall estimates are vertical reflectivity profile, drop size distribution and hence the *Z-R* relationship, anomalous clutter, attenuation by precipitation, beam blockage and temporal sampling errors (G. Villarini, & Krajewski W. F., 2010). In mid-latitudes [1] (23°26'22" N and 66°33'39"N, and between 23°26'22"S and 66°33'39"S) the most important of these

[1] http://en.wikipedia.org/wiki/Middle_latitudes

errors are vertical profile reflectivity, the *Z-R* relationship as a consequence of drop size distribution and attenuation of beam by precipitation (Holleman, 2006). Of these three, the current study will look at the *Z-R* relationship and attempt to adequately specify it for the Water Board districts of the Regge and Dinkel in order to minimize its contribution to the error budget. Previous studies have shown and recommended reduction of bias between radar and rainfall through finding the best fit *Z-R* for an area (Fournier, 1999; Leijnse et al., 2007; Mapiam, 2008; van de Beek et al., 2010).

The *Z-R* relationship can be calibrated in three ways. Firstly, a disdrometer can be used to determine drop size distribution for the rain rate calibration (Alfieri, et al., 2010). Another approach is to determine the *Z-R* relationship directly by matching the measured radar reflectivity and rainfall (Biggs & Atkinson, 2011). The first method has the advantage of reducing errors associated with measuring rain rate aloft, but has the disadvantage that the disdrometer is also associated with errors and according to Wilson, J. W. and Brandes, E. A. (1979). Actual measurements of the drop size distribution are highly uncertain.

The advantage of the second approach is its simplicity, but this is associated with errors due to the difficulty in exactly selecting a volume in the atmosphere corresponding to ground measurements and also differences in temporal resolution between the techniques (Alfieri, et al., 2010). In order to minimize this effect rain gauge rainfall is accumulated over a selected time scale and radar reflectivity is averaged over a selected kernel of pixels centred at the point of ground measured for a similar time scale (Alfieri, et al., 2010). The third method involves probability matching which obtains the best fit parameters of reflectivity and rain rate by matching the cumulative distribution functions of reflectivity with that of rainfall (Atlas *et al.*, 1990; Li & Shao, 2010; Rosenfeld *et al.*, 1994; Rosenfeld *et al.*, 1993).

Currently, the *Z-R* relationship used for the Regge and Dinkel by KNMI is the same one used for the whole of the Netherlands. The accuracy of this approach in estimating rainfall for the Regge and Dinkel has not yet been assessed. There are, however, 18 rain gauges operated by the Water Board such that the estimates from radars should be close to these in-situ measurements of rainfall. There is, therefore, the opportunity to calibrate the radar using in-situ measurements in order to establish a *Z-R* relationship that fits the climatology and rainfall types within the districts of the Regge and Dinkel. The intention is to reduce errors in the radar based rainfall estimates, specifically those caused by imperfections in the *Z-R* relationship, and the eventual goal is to enhance the reliability of rainfall estimates over the catchment area of the Regge and Dinkel for improved monitoring capabilities that lead to skilful water resources management.

1.2. Objectives

The main objective is to improve the accuracy of radar rainfall estimates for the Water Board district of the Regge and Dinkel through calibration of the reflectivity-rain rate (*Z-R*) relationship using in-situ measurements by rain gauges.

The following specific objectives can be formulated:

- Define the *Z-R* relationships specific for the Regge and Dinkel area using the local rain gauges operated by Water Board Regge and Dinkel;
- Identify the time dependency (e.g. seasonal and inter-annual) in the *Z-R* relationships for the area of the Regge and Dinkel;
- Establish the accuracy of rainfall estimates over the Regge and Dinkel district that is currently available from the nationwide calibration radar measurements;
- Evaluate the (improved) accuracy of the radar based rainfall estimates obtained with the Regge and Dinkel district specific calibrated *Z-R* relationships.

1.3. Research questions

- What is the accuracy of radar rainfall estimates obtained with the nationwide calibrated *Z-R* relationship as validated against in-situ gauge measurements?
- Does the *Z-R* relationship display a seasonal or inter-annual dependence?
- Will the uncertainties in radar based rain estimates be reduced when the *Z-R* relationship is defined based on local gauges?

2. STUDY AREA AND DATA SETS

2.1. Description of the study area

The study area is located within the Overijssel province (Figure 2) in the eastern part of the Netherlands (lon. 52^{o}08’ - 53^{o}31’N and lat. 6^{o}23’ - 7^{o}04’E). The area (approximately 1374 km^{2} in size) has little relief and is covered by grasslands, agricultural fields and forested areas. It lies in the temperate zone of the northern hemisphere and experiences typically cool dry summers and mild wet winters, which are occasionally cold. December, January and February are the coldest months with average temperatures of 0.5 ^{o}C, -0.3 ^{o}C and -0.8 ^{o}C, respectively (Encyclopedia of the Nations, 2011).

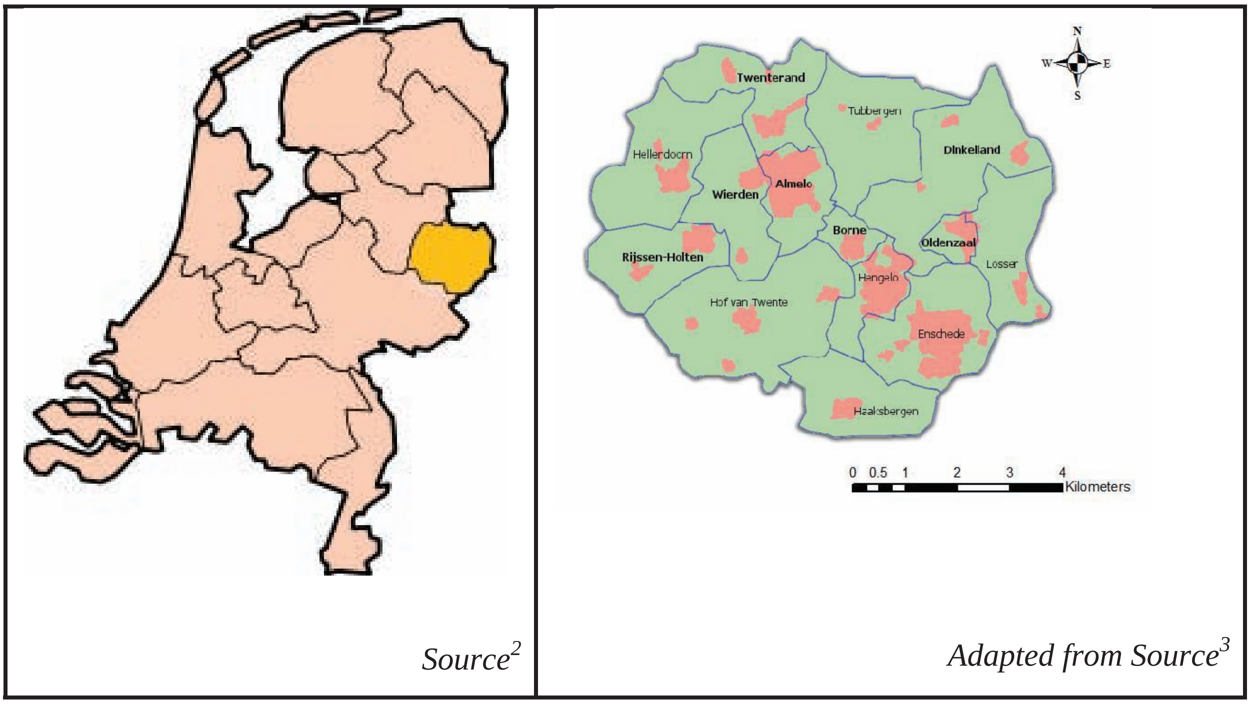


Figure 2: Map of Netherlands (left) showing position of the Twente Area (in orange) and Map of Twente (right)

The average temperature is 2 ^{o}C in January and 19 ^{o}C with annual average of about 10 ^{o}C (Encyclopedia of the Nations, 2011). Clouds generally appear every day and rainfall is evenly distributed through the year with on average a sum of about 765 mm and a somewhat drier period from April to September (Encyclopedia of the Nations, 2011).

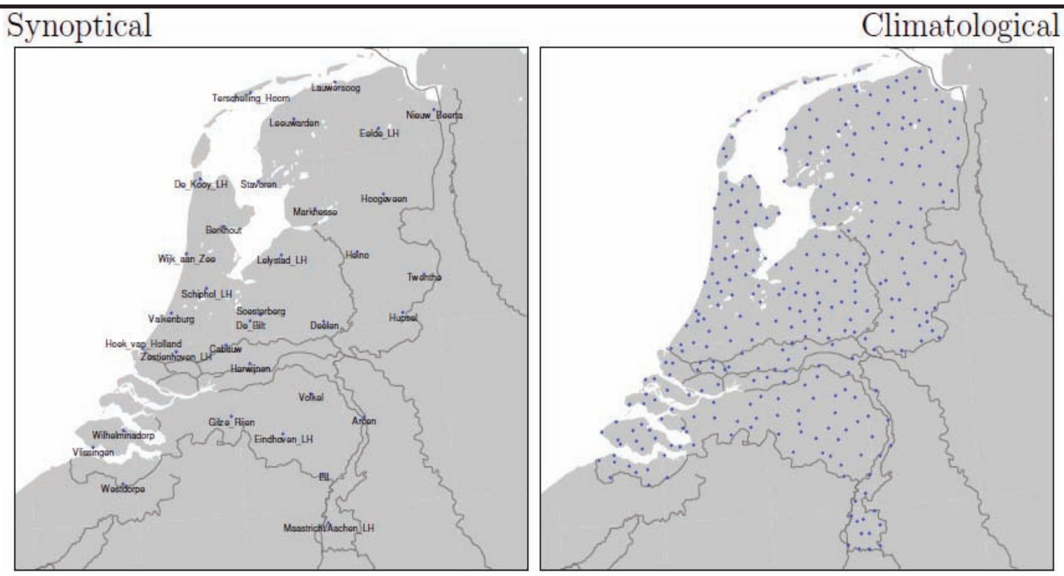
[2] http://en.wikipedia.org/wiki/Twente

[3] http://www.google.nl/imgres?q=MapTwente+Netherlands&hl=nl&biw=1366&bih=667&tbm=isch&tbnid=L7Cwv2OLbFSR0M:&imgrefurl=http://development.thar.nl/page/Twente&docid=t5_pOyE3Wh8kjM&itg=1&w=555&h=457&ei=2KnpTuLNCc6XOqXDxLkI&zoom=1&iact=hc&vpx=381&vpy=229&dur=687&hovh=134&hovw=163&tx=122&ty=84&sig=10897772037138031Enschede West3&page=1&tbnh=134&tbnw=163&start=0&ndsp=19&ved=1t:429,r:1,s:0

The Water Board of Regge and Dinkel is responsible for management of the water quality and quantity in the Twente region. They are concerned with ensuring smooth flow of water and monitoring the quantities thereby enhancing the safety of citizens against water related catastrophes such as floods and drought (Regge en Dinkel, 2011).

2.2. Rain gauge network

A volunteer rain gauge network (Figure 3b) consists of about 325 stations that record rainfall manually and report the measurements daily. They use conventional rain gauges with horizontal entry area of 0.2 m^2 and measuring cylinder with a resolution of 0.1 mm and observation accuracy is exceeds 0.1 mm (Holleman, 2006). In addition, the KNMI operates a network of 35 automated weather stations (Figure 3a) with rain gauge instrumentation of which only one is located in the Twente region.



a) b)

Source (Holleman, 2006)

Figure 3: (a) The Dutch national synoptic and (b) the volunteer rain gauge network

In case of rain events the stations record rainfall amounts with a resolution of 10 minutes (Leijnse, et al., 2007). They use the position of the floater in the cylinder to determine amount of rainfall (Holleman, 2006). Rain gauge data has been obtained from the Water Board from the 18 gauges. These are not part of the KNMI network.

Tipping bucket rain gauge collects rainfall in a funnel that is suspended on a lever which tips when a set amount of rainfall is exceeded and the tip is converted into an electrical signal. The product of the number of tips and the pre-set amount of rainfall required for the funnel to tip converts to amount of rainfall measured. A standard rain gauge collects water in a graduated cylinder at a low temporal resolution and is emptied and read manually. It has an overflow outer cylinder which collects excess rainfall when the graduated cylinder is full[4].

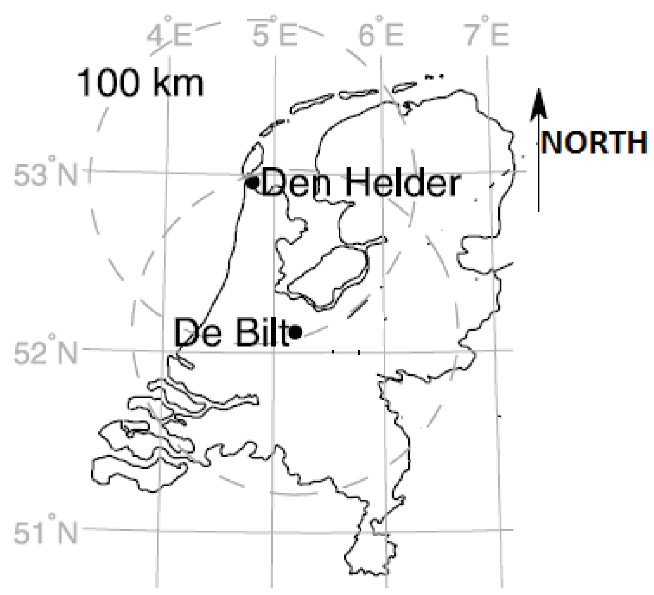
[4] http://en.wikipedia.org/wiki/Rain_gauge

Figure 4: Type of rain gauges used by the Water Board

The Water Board uses the type of automated tipping bucket rain gauges shown in Figure 4. The set up reduces the effect of wind and splashing on accuracy of the gauges. The Water Board records rainfall at places indicated on the below (Table 1). The data recorded at various sites have been collected over different periods of time the longest was the rain gauge at Goor with 11 years of data and the shortest being at Nijvedal with about a year of data.

2.3. Rain radar data set

The Royal Netherlands Meteorological Institution (KNMI) operates two C-Band radars (Figure 5) located in De-Bilt (52.10 ^{o}N and 5.18 ^{o}S) and Den Helder (52.96 ^{o}N and 4.79 ^{o}S) and covering the whole Netherlands (Leijnse, et al., 2007) will be used. The position of the Regge and Dinkel district is to the far east of the country, a distance of at least 100 km from the De Bilt radar. Holleman (2006) remarked that the radar rainfall estimates become unreliable with increasing range and that at long ranges rainfall is under-estimated.



Source (Leijnse, *et al.*, 2007)

Figure 5: Two C-Band radars operated by KNMI

The C-band radars use microwaves of frequency of 5.6GHz and mean field bias varies depending on meteorological conditions (Holleman, 2006). They have a spatial resolution of 2.5km and a radar reflectivity factor map is received at time steps of 5 minutes (Holleman, 2006; Leijnse*, et al.*, 2007). This reflectivity factor (*Z* in mm^6/m^3) is converted into a rain rate (*R* in mm/hr) using the so-called *Z*-*R* relationship [or power law],

$$Z = aR^b \tag{1}$$

where *a* and *b* are empirical coefficients. Standard radar rainfall obtained from KNMI are produced using coefficients *a* and *b* equal to 200 and 1.6, respectively (Leijnse, et al., 2007). The accuracy has been assessed for the whole of the Netherlands using 35 automatic rain gauges on the synoptic network of KNMI (Figure 3(a)) which excludes gauges operated by the Water Board. However, for the Regge and Dinkel district the accuracy of radar based rainfall estimates is not thoroughly validated as yet because the rain gauges operated by the Water Board Regge and Dinkel are not included in the KNMI network.

3. PRE-PROCESSING

3.1. Radar dataset pre-processing

Pre-processing followed the flow chart in Figure 6. The radar data was obtained from KNMI in hdf5 netCDF format at a spatial resolution of 2.5 km and then processed to GeoTif format for further analysis. The radar data was averaged to hourly intervals. A point map showing the location of the rain gauges was used to locate radar pixels coinciding with these locations. Hourly radar reflectivity data was extracted from 9 points spatially using a 3 by 3 window. This section was done using IDL programming in order to speed up the process.

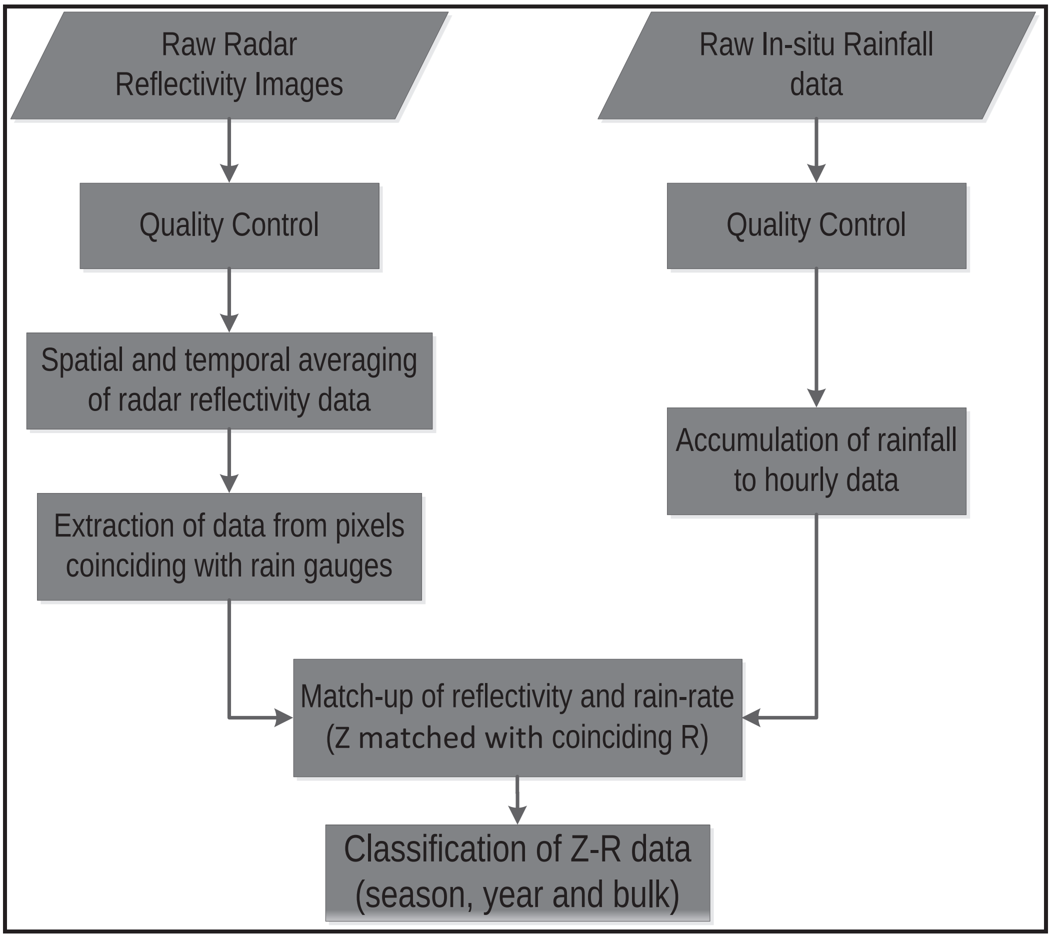


Figure 6: The summary of steps followed during pre-processing

3.2. Gauge data pre-processing

Rain gauge data were obtained from the Water Board Regge and Dinkel at 20 minutes resolution for 18 sites. The sites had different data lengths and for this reason this study uses data from only 9 sites with periods of lengths shown in Table 2. Since the *Z-R* relationship varies with time stations were selected which had data for most of 2006 to 2010 to avoid mixed trends by using data from much separated years as effects of climate change were suspected between the periods. The other reason was that the period 2006 to 2010 was to be used and after quality check these 9 locations were found to be with reliable data. The data had some gaps and double entries between the period for some of the months, therefore, a comprehensive quality control was conducted manually in excel to improve the reliability of the data. The use of periods with inconsistencies was avoided throughout. The data were then computed from 20 minute intervals to a time step of one hour for each location.

Table 1: In-situ rainfall measure sites in the Regge and Dinkel area used for this study

Site	Latitude	Longitude	Period covered by provided data
Goor	52.25	6.57	January 2000 to October 2011
Losser	52.26	7.02	November 2003 to October 2011
Hammerflier	52.48	6.54	December 2001 to October 2011
Wierdenseveld	52.38	6.52	May 2003 to October 2011
Denekamp	52.39	7.04	November 2003 to October 2011
Enschede West	52.25	6.80	December 2005 to October 2011
Almelo Sumpel	52.34	6.63	April 2005 to October 2011
Tubbergen	53.38	6.71	September 2004 to October 2011
Den Ham	52.47	6.48	July 2006 to October 2011

3.3. The match up of reflectivity and rain rate data

The radar data were obtained using a kernel of 3 by pixel centred above each gauge in a way which is explained in section 8.2.1 of Chapter 8. This was done for the 9 sites for the period from 2006 to 2010. The intention was to use the data from 6 sites for calibration and the rest of the data for validation. The *Z-R* data were then organized into 3 classes upon which the *Z-R* was to be established. These classes were the time independent (termed 'bulk' in this study), the seasonal and yearly *Z-R* data sets. The *Z-R* relationship should also specify the averaging time on which it depends because different averaging time produces different *Z-R* relationships (Atlas*, et al.*, 1990). Therefore, in this study a time step of one hour was used.

4. IN-SITU MEASUREMENT ANALYSIS

4.1. Temporal trends in rainfall

Analysis of the rainfall measurements was done for the stations at Goor, Losser, Den Ham, Denekamp, Wierdenseveld, Enschede West, Tubbergen, Hammerflier and Almelo Sumpel for the period 2006 to 2010. In each of the analysis average rainfall for all the locations was calculated and assumed to represent the mean aerial average. These averages were calculated for each month, season and year. Figure 7 shows that the study area receives rainfall amounts varying from 25 to 120 mm/month throughout the year. The month of April is the driest with an average of 25 mm while the wettest month is August with 120 mm of rain. The monthly rainfall for the other months for the other months ranges from 30 mm to 80 mm.

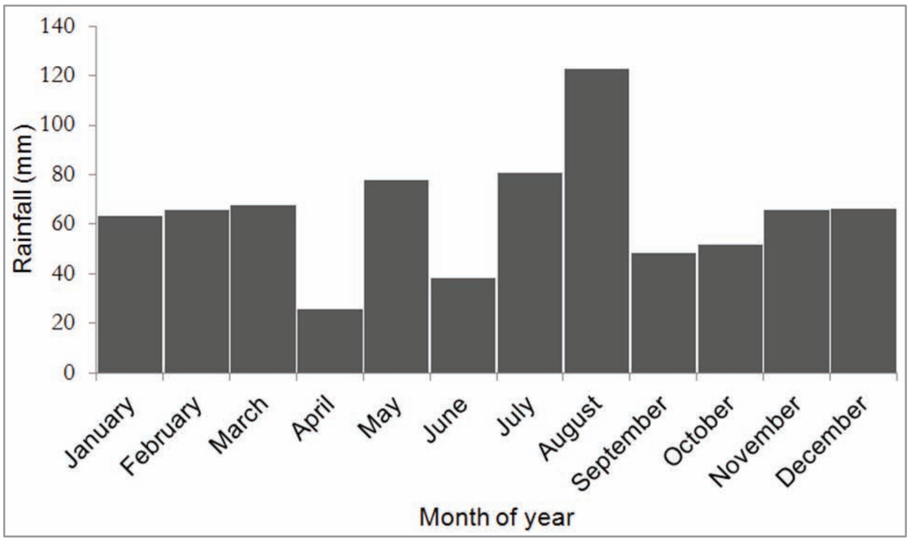


Figure 7: Areal average monthly rainfall for the Regge and Dinkel for period 2006-2010

4.2. The spatial distribution of rainfall

Figure 8 shows the variability in rainfall over the study area considering the distribution based on the 9 sites used in this study. The average annual rainfall ranged from 570 mm to 880 mm. The highest amount was 876.5 mm received at Losser while the least was received at Goor with 578 mm. Goor and Wiedenseveld were the only two sites which received an average rainfall amount less than 700 mm/ year.

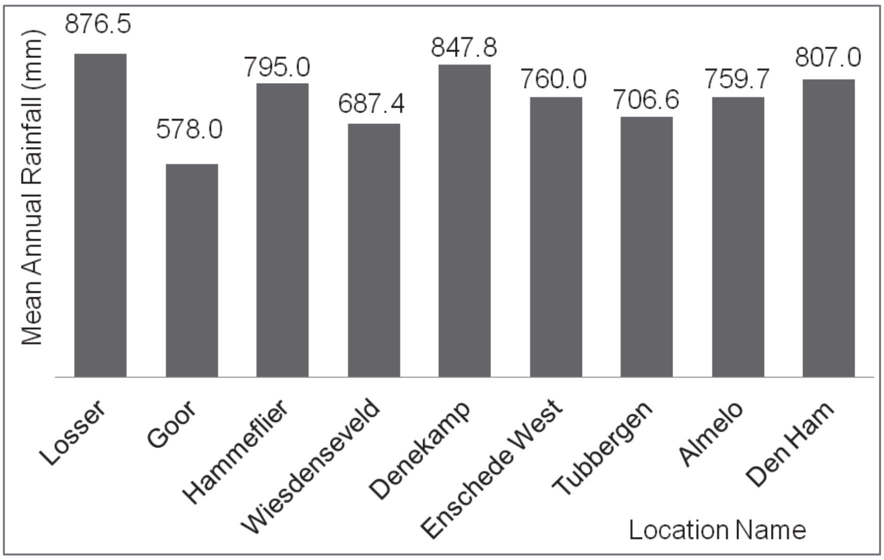


Figure 8: Average Annual rainfall for the period 2007 to 2010

The average rainfall figures were confirmed with a technical report from KNMI (Buishand *et al.*, 2009) which says that rainfall over the Netherlands ranges between 700 and 900 mm/year. The average obtained in this study was 681.2 mm/year which compares well with range also given that for 7 of the 9 sites used it agreed with the range.

There was a general increase of amounts of rainfall received annually as we move eastwards over the Regge and Dinkel area (Figure 9). Goor to the extreme South-west received an annual average of 578 mm during the period 2006 to 2010. On the other hand, Denekamp which is to the extreme East of the area received an average of 847.8 mm during the same period. Losser which is also on the eastern margin of the area received had the highest (876.5 mm) value for the same period. This makes a clear difference of almost 300 mm between Losser and Goor indicating this increasing trend eastwards. This difference is most likely associated with the subtle relief in the landscape. For instance, with a prevailing wind coming from the west Goor is situated in the shadow of the Salandse Heuvelrug which could lower rainfall amounts received there. Based on hourly data, the low value obtained for Goor was not due to missing data because there were only 3 hours of missing data for the five years considered. The place displayed a decreasing trend in rainfall over the five years considered (Appendix 3).

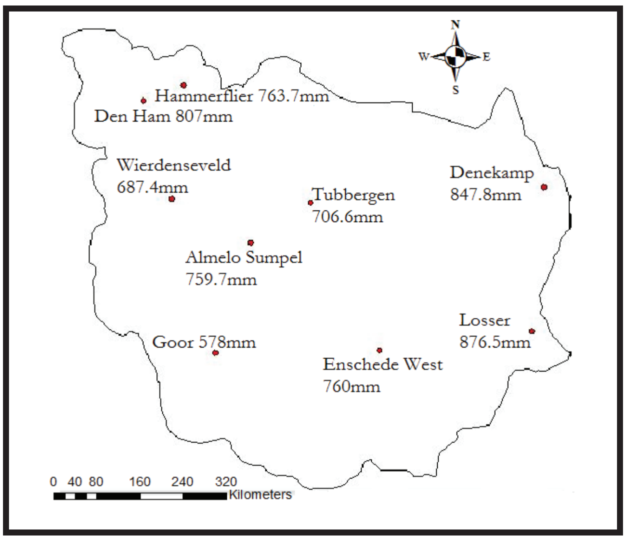


Figure 9: Spatial distribution of rainfall in the Regge and Dinkel area

4.3. Rainfall intensities

The most intense rainfall event was 52.7 mm received in one hour at Enschede West in 2007. Although maximum intensity displayed high temporal and spatial variability, there was no trend displayed over the years (Table 3). The maximum intensities recorded over the study period were mostly below 20 mm/hour.

Table 2: Maximum intensity received for a particular year (mm/hour)

Location	2006	2007	2008	2009	2010
Wiedenseveld	13.1	12.0	23.9	10.6	17.0
Denekamp	10.6	15.0	11.0	11.8	18.6
Tubbergen	30.1	23.4	33.7	19.9	13.2
Enschede West	29.7	52.7	11.7	11.1	8.8
Den Ham	-	16.0	16.0	20.6	28.2
Almelo	15.1	12.1	17.4	11.8	19.7
Hammerflier	-	12.6	10.8	15.4	17.2
Losser	13.8	16.1	12.2	11.2	22.3
Goor	15.2	13.5	10.5	14.8	14.2

The number of events of intensity greater than 5 mm in 20 minutes showed a general decrease with time especially the sites at Goor, Denekamp and West Enschede (Figure 10) [for the average of all locations trend in Appendix 1 shows a slight decrease with r-squared of 0.0691]. On the other hand, there are also sites, e.g. Losser and Hammerflier, where the number of events per year showed an increase.

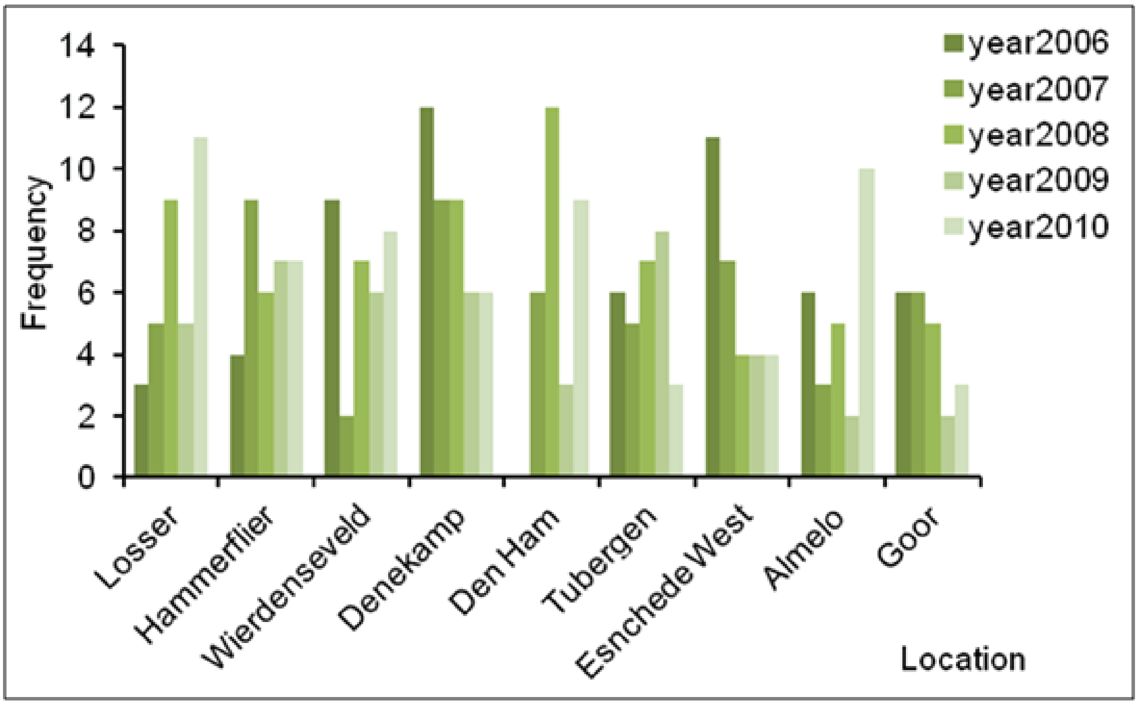


Figure 10: The number of rain events per year more than 5 mm recorded at the rain gauges situated in the Regge and Dinkel district.

5. THE STATISTICAL MEASURES OF ACCURACY

The measures of accuracy most commonly used in rainfall estimation accuracy determination include root mean square factor (RMSF), root mean square error (RMSE), mean absolute error (MAE), mean relative error (MRE) and bias (Alfieri*, et al.*, 2010; Biggs & Atkinson, 2011; Borga, 2002; De Bruijn & Brandsma, 2000; Li & Shao, 2010; Mapiam, 2008; Piman *et al.*, 2007; van de Beek*, et al.*, 2010). We therefore present below how these are used to measure accuracy.

$$RMSF = exp\left(\sqrt{\{\frac{1}{n}\sum_{i=1}^{n}[In(\frac{R_i}{G_i})]^2\}}\right) \tag{2}$$

Where R_i and G_i are radar and gauge rainfall (mm), respectively, at observation *i* and *n* is the number of observations. The closer RMSF to 1 the more accurate the estimates (De Bruijn & Brandsma, 2000).

$$\mathrm{RMSE} = \sqrt{\left\{\frac{1}{\mathrm{N}}\sum_{\forall \mathrm{t_i}}\sum_{\forall \mathrm{j}}(\mathrm{E_{t_{i,j}}} - \mathrm{M_{t_{i,j}}})^2\right\}} \tag{3}$$

$$MAE = \frac{1}{N}\sum_{\forall t_i}\sum_{\forall_j}\left|E_{t_i,j} - M\right| \tag{4}$$

$$BIAS = \frac{1}{N}\sum_{\forall t_i}\sum_{\forall_j}\left(E_{t_i,j} - M_{t_i,j}\right) \tag{5}$$

$$MRE = \frac{1}{N}\left(\frac{\sum_{\forall t_i}\sum_{\forall_j}\left|E_{t_i,j} - M_{t_i,j}\right|}{M_{t_i,j}}\right) \tag{6}$$

$M_{\mathrm{t_{i,j}}}$ is the measured rain-rate or radar reflectivity at time t_i from the j-th rain gauge corresponding with $E_{\mathrm{t_{i,,i}}}$ the estimated rain rate or reflectivity obtained at the same place and time. These statistical measures of accuracy were used in this study for calibration and for validation. The other measures of accuracy such as bias correction factor will be introduced later.

6. OPTIMIZATION

The fitting of reflectivity and rain-rate data to an exponential relationship is done by minimizing a cost function, which is referred to as the optimization process. Details about reflectivity and rain-rate data used will be discussed in the chapters about window probability matching method and calibration of the *Z-R* relationship that will follow. In this study optimization was done by minimizing the root mean square error and criteria used to select this will be discussed in the section about selection of cost function. Rainfall intensity is estimated from the power law as a function of reflectivity as

$$R_{Modelled} = \left(\frac{Z}{a}\right)^{\left(\frac{1}{b}\right)} \tag{7}$$

Similarly so reflectivity can be modelled as

$$Z_{Modelled} = aR^{b} \tag{8}$$

The optimization process can be setup for minimizing either the errors in the modelled rainfall or in the in the modelled reflectivity. In other words, we seek for coefficients *a* and *b* for which

$$(Z_{Modelled} - Z_{measured}) \rightarrow 0 \tag{9}$$

When optimization is done based on modelled rain-rate the effort is to achieve the condition that

$$(R_{Modelled} - R_{measured}) \rightarrow 0 \tag{10}$$

The cost functions that can be used for optimization are the RMSE, bias, MAE, RMSF and the mean relative error (MRE) discussed in Chapter 5. Except for the root mean square factor which needs to be as close to 1 as possible, the rest of the cost functions should be brought as close to 0 as possible. Although many cost functions can be used to find the best fit, it was found necessary to test each one of them and identify the best to be used for all the calibrations. Different cost functions give different weight to errors made over the entire range of the rain-rates.

7. REFLECTIVITY-RAIN RATE [Z-R] RELATIONSHIP

The ground weather radar is an active sensor that transmits microwave radiation and measures radiation that is scattered back to the antenna of the radar. Hydrometers in the atmosphere scatter the transmitted microwaves by an amount that is proportional to the density of these water particles that scatter the radiation. The principle of detecting rain-rate using radar is portrayed in Figure 11.

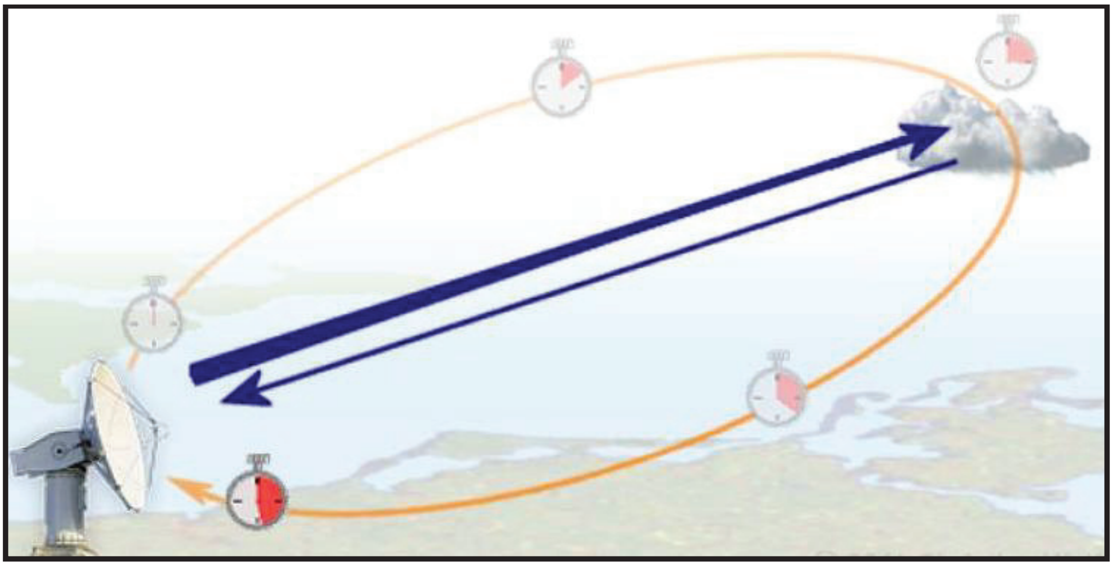


Figure 11: Measurement of back scattered radiation by a ground weather radar[5].

Backscattered radar power from precipitation is proportional to the sixth power of particle diameter in a volume illuminated hence radar reflectivity is defined as,

$$Z = \sum_i N_i D_i^6 = \int_0^\infty N(D) D^6 dD \qquad (11)$$

where N_i [in m^{-3}] is the number of drops per volume of air with diameter D_i and $N(D)$ [in m^{-3}] is the number of drops with diameter between D [in mm] and $D+dD$ in a unit volume (Wilson & Brandes, 1979). Assuming no vertical air motion, rain-rate is related to D as

$$R = \frac{\pi}{6} \int_0^\infty N(D) D^3 V_t(D) d(D) \qquad (12)$$

where $V_t(D)$ [in cms^{-1}] is the terminal velocity that is approximated to be $V_t(D) = 1400 D^{1/2}$ (Spilhaus, 1948). Substituting the Marshall and Palmer exponential drop size distribution equation (Marshall, 1948) into (1) and (2) and using the empirical relationship between V_t and D obtained

$$Z = aR^b \qquad (13)$$

where Z is the reflectivity factor [in mm^6/m^3], R the rain rate [in mm/hr] while *a* and *b* are empirical coefficients (Wilson & Brandes, 1979) obtained using non zero rain rate and reflectivity matchup measurements (Alfieri, et al., 2010). The most commonly used value of *a* is 200 but it can vary between 0 and 500 while the most common value of *b* is 1.6 but it has a range of 1.0 to 2.0 (Shelton, 2009). Figures for the UK show that *a* lies anywhere between140 for drizzle, through 180 for frontal rain, to 240 for heavy convective storms while in an Alpine setting *a* can be 500 for thunderstorms (Strangeways, 2007).

[5] http://www.radartutorial.eu/15.weather/pic/radarprinzip1.print.jpg

Table 3: Examples of variations in *Z-R* with space and rainfall types obtained from literature

Source	Place	Rainfall type	*a*	*b*
(Steiner et al., 1995)	Australia	Tropical precipitation	230	1.25
(Steiner, et al., 1995)	Darwin, Australia	Gauge adjusted convective	82	1.47
(Steiner, et al., 1995)	Darwin, Australia	Gauge adjusted stratiform	143	1.5
(Steiner, et al., 1995)	Darwin, Australia	All types (bulk)	167	1.25
(Alfieri, et al., 2010)	North Western Italy	All types (bulk) (non-linear regression)	79.1	1.81
(Alfieri, et al., 2010)	North Western Italy	All types (bulk) (linear regression)	106	2.02
(Alfieri, et al., 2010)	APA Piemont, Italy	All types (bulk)	300	1.5
(Ulbrich, 1999)	South Carolina, US	All types (bulk)	300	1.4
(Ulbrich, 1999)	North Carolina, US	Heavy (recommended)	250	1.2
(Marshall, 1948)	Widely used Globally	All types (bulk)	200	1.6
(Wilson & Brandes, 1979)	Oklahoma, US	Showers, thundershowers	200	1.6
(Wilson & Brandes, 1979)	Florida, US	Showers, thundershowers	300	1.4
(Wilson & Brandes, 1979)	England	Showers, thundershowers	200	1.6
(Wilson & Brandes, 1979)	New York, US	Showers, thundershowers, Stratiform	200	1.6
(Wilson & Brandes, 1979)	Illinois, US	Showers, thundershowers	300	1.35
(Li & Shao, 2010)	Canada	Convective rain showers	32	1.65
(Piman, *et al.*, 2007)	Mae Chaem North of Thailand	Orographic	18.05	1.45
(Atlas, *et al.*, 1990)	German	Winter (Zmin=21dB at 200km)	266	1.41
(Atlas, *et al.*, 1990)	German	Autumn (Zmin=21dB at 200km)	252	1.50
(Atlas, *et al.*, 1990)	German	Summer (Zmin=21dB at 200km)	276	1.47
(Atlas, *et al.*, 1990)	German	Fall (Zmin=21dB at 200km)	247	1.42

Table 3 shows *Z-R* relationships which were obtained in other studies and that they change with time and also from place to place (Zmin is the threshold of the reflectivity used for calibration). The *Z-R* relationships for the Regge and Dinkel are, therefore, expected to be different from those of other parts of the world and of the Netherlands because of variability due to climatology and rainfall types predominantly received across the world. Due to climate change, drop size distribution of rain events in Netherlands could be changing and thus changing the *Z-R* relationship as a result. Therefore, the dependency of the *Z-R* relationship on time will be evaluated.

8. CALIBRATION OF THE Z-R RELATIONSHIP

8.1. Summary of the overall calibration process

Because the nationwide calibration for the radar based rainfall estimates could be different from that for the Regge and Dinkel district, the *Z-R* relationships will be developed for this district using the rain gauge and reflectivity matchups obtained following the flow chart in Figure 12. The window probability matching method (Rosenfeld, *et al.*, 1994) was used to come up with the reflectivity-rain-rate (*Z-R*) relationships. The *Z-R* relationships obtained were compared with the Marshall and Palmer *Z-R* relationship currently used by KNMI over the entire Netherlands (Holleman, 2006; Leijnse, *et al.*, 2007). The comparison assisted in evaluating whether redefining the *Z-R* relationships improves the accuracy of radar rainfall estimates for the area when compared with in-situ measurements by the Regge and Dinkel municipality. The *Z-R* relationships were calibrated for the time independent (bulk) which included all years and all seasons. Calibration was also done for different seasons and years separately since the *Z-R* relationships change with time (Alfieri, *et al.*, 2010).

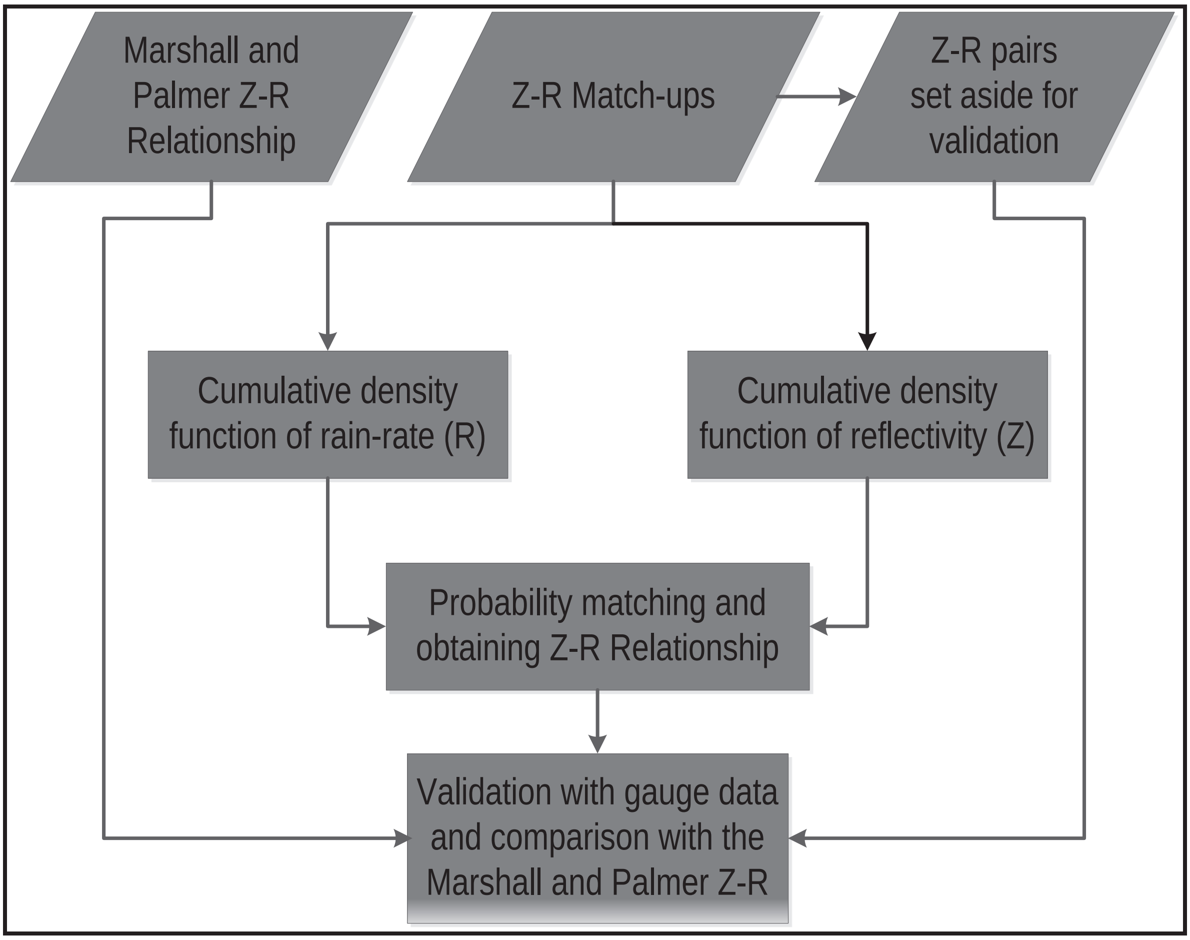


Figure 12: Determination and validation of the *Z-R* relationship

Due to difficulties in defining *Z-R* pairs referring to the same volume of atmosphere sampled, rainfall measurements are accumulated over hourly periods and radar reflectivity are spatially averaged over 3 by 3 pixel windows (Figure 9) and temporally over hourly intervals (Alfieri, *et al.*, 2010; Fabry *et al.*, 1994; Mapiam, 2008).

8.2. The window probability matching method

The window probability matching method was established by Rosenfeld et al., (1994) to remove constrains of the general probability matching method (Calheiros & Zawadzki, 1987) which required regions with homogeneous rainfall. The method eliminates timing errors because it does not make use of actual time at which each pair of rain-rate (*R*) and reflectivity (*Z*) occurred assuming that the radar observed reflectivity has the same probability of occurrence as the rain-rate measured by gauges (Atlas*, et al.*, 1990; Calheiros & Zawadzki, 1987; Rosenfeld*, et al.*, 1993). The method ensures that the cumulative density function of radar derived rain-rate matches with that derived from the gauges resulting in estimates of cumulative rainfall from the radar which are consistent with those from the gauges. The advantage of this method is that it eliminates errors associated with errors in timing. In this study, there were no constrains of data shortage as high resolution radar reflectivity and rainfall data described in chapter 2 of a period of 5 years was available for use.

In this study the probability matching method was implemented in the following steps;

I. Extraction of reflectivity data from a kernel of 3 by 3 pixels centred above the location of the rain gauge
II. Matching of cumulative density function (CDF) of reflectivity with that of rain-rate
III. Determination of the *Z-R* relationships using *Z-R* pairs adjusted to the climatology of the Regge and Dinkel obtained from CDF matching

Each of these steps will now be explained in detail in the discussion that follows.

8.2.1. Extraction of reflectivity data from a kernel of 3 by 3 pixels

This step was part of pre-processing already explained above but its physical meaning will be well understood after this stage. It is difficult to identify a volume in the atmosphere that contributes to the rainfall received at the location of a gauge on the ground. In order to ensure collocation and synchronization of radar and gauge measurements, each rainfall measurement on the ground is made to coincide with reflectivity obtained by spatially averaging reflectivity of pixels found within a 3 by 3 kernel centred above the rain gauge (Figure 13). The window probability matching method uses that approach in correlating rainfall on the ground with radar reflectivity and assumes that rain drops fall vertically to the ground (Rosenfeld*, et al.*, 1993).

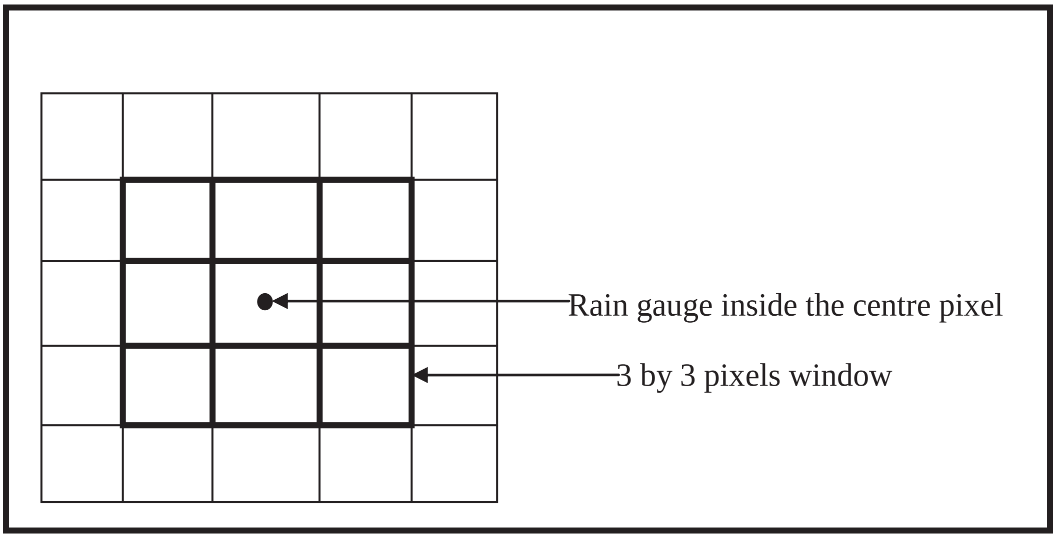


Figure 13: Example of a 3 by 3 pixels window centred at the pixel coinciding with the position of a rain gauge (Adopted idea (Piman*, et al.*, 2007))

The kernel size must be of an adequate size to represent the rainfall depth within the radar field and Rosenfeld, et al (1993) used a 3 by 3 pixels window (see example in Figure 14), an approach followed in this study. The hourly radar reflectivity was, therefore, averaged over the kernel of 3 by 3 pixels to coincide with hourly rainfall measured by the rain gauge corresponding with it. The pairs obtained in this way were assumed collocated and synchronous although the window probability matching method only needs collocation and synchronization to identify where and when there is rainfall. The rest of the calibration is not affected by collocation and synchronization because the method does not use the actual time at which the pairs were obtained as will be soon explained.

8.3. Matching of cumulative density functions of reflectivity and rain-rate

The method does not use pairs of reflectivity and rain-rate obtained from collocated and synchronous radar reflectivity and gauge measurements. It makes use of reflectivity Z_i and rain-rate R_i such that cumulative distribution function of *Z* and that of *R* would match.

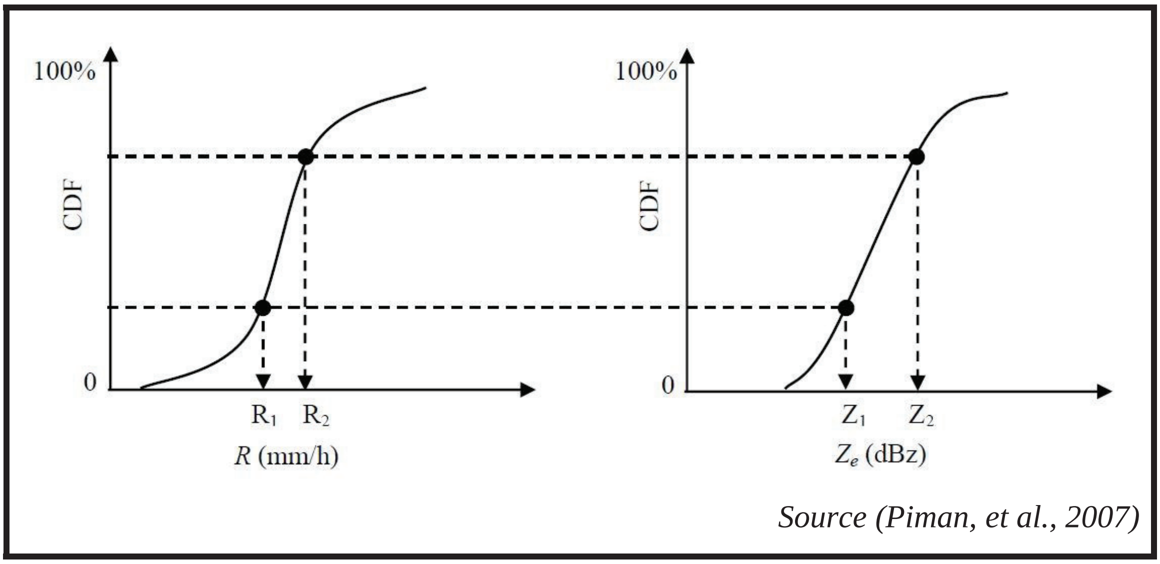


Figure 14: The probability matching method

The matching pairs Z_i and R_i are selected as shown in Figure 14 at the ith percentile of the cumulative density function of reflectivity and that of rain-rate such that

$$\int_{R_i}^{\infty} P(R)dr = \int_{Z_i}^{\infty} P(Z)dz \qquad (14)$$

The cumulative density functions of rain-rate (*R*) and reflectivity (*Z*) must come from the same sample for which the relationship should be calibrated. The matching pairs Z_i and R_i obtained from the cumulative density function as described already are then used to establish the reflectivity rain-rate relationship. In this way pairs obtained are adjusted to all factors that affect rainfall over the study area which include drop size distribution.

8.4. Determination of the *Z-R* relationships

The process of determining the *Z-R* relationships was finally done in three steps which are

I. Selection of cost function to be minimized
II. Setting of threshold of reflecting to correspond with minimum measurable rain-rate
III. Actual determination of different *Z-R* relationships

Each of the steps and the results obtained are explained in the discussions that follow.

8.4.1. Selection of the cost function to be used for fitting data to the power law

As indicated above in section 6.1.1, there are several measures of accuracy that can be used during optimization to obtain best fit coefficients (*a* and *b*) of the *Z-R* relationships. One of the conditions used in this study was to obtain the coefficients *a* and *b* which would give minimum values of RMSE, MAE, MRE and bias and at the same time giving RMSF close to 1.0. This followed the work of Mapiam (2008) in which coefficients *a* and *b* giving the minimum of mean error, MAE, RMSE and bias were sought for. Therefore, in this study one cost function was selected such that when minimized coefficient *a* and *b* are obtained at minimum values of the other errors.

In order to select the best cost function to use, the RMSE, RMSF, MAE, bias and MRE were minimized. At this stage, one cost function was minimized at a time and there were no constraints used. This was done before setting of the reflectivity threshold, therefore, the threshold of 7 dB corresponding with a minimum rain-rate of 0.1 mm/hr adopted from Holleman (2006) was used. The highlighted column (light grey) in Table 4 shows the cost function minimized at a particular optimization run while the rows that follow show the resulting *a* and *b* coefficients and the magnitude of the other statistics calculated using both reflectivity and rain-rate estimates and measurements.

The highlighted rows (dark grey) in Table 4 present the optimization run which resulted in relatively good performance according to all statistics. The other cost functions were giving large errors and even when using bias in reflectivity as a cost no convergence was obtained. The bias in reflectivity alone cannot be used for the optimization. As shown in Table 4 root mean square error in reflectivity, RMSE in rain-rate, MAE in reflectivity and MAE in rain-rate converged at higher accuracy than the other cost functions. The accuracy of these four did not show much difference. The coefficients *a* and *b* obtained using these four were also not very different.

However, when closely compared it was seen that using RMSE in either rain-rate or reflectivity yields similar coefficients *a* and *b* at almost equally low values of the other measures of accuracy. The results obtained using MAE in reflectivity were also closely comparable to the ones using MAE in rain-rate. At this stage it was still not yet easy to identify which one of the best four to be used as a cost function. Therefore, further analysis was done using graphical display shown in Figure 15 and comparison of the effect of the selected cost function on the magnitude of errors at different rain-rates was done.

Table 4: Optimizing using different cost functions

Optimizing Cost Function	RMSE in *Z* mm^6/m^3	MAE in *Z* mm^6/m^3	BIAS in *Z* mm^6/m^3	MRE in *Z* mm^6/m^3	RMSF	RMSE in *R* mm/hr	MAE in *R* mm/hr	BIAS in *R* mm/hr	MRE in *R* mm/hr	Cumulative Rainfall Difference	*a*	*b*
RMSE in Z mm^6/m^3	10.789	6.751	0.201	0.187	1.339	0.076	0.062	0.016	0.136	0.370	67.417	1.518
MAE in Z mm^6/m^3	12.122	6.120	2.427	0.180	1.329	0.080	0.059	0.026	0.132	0.592	67.400	1.503
Bias in Z mm^6/m^3	-	-	-	-	3.603	1.422	1.029	0.241	1.029	5.552	75.992	617.056
MRE in Z mm^6/m^3	34.693	16.197	13.636	0.173	1.285	0.198	0.114	0.086	0.130	1.972	67.047	1.424
RMSF	46.981	22.911	14.083	0.210	1.218	0.303	0.174	0.075	0.161	1.724	75.241	1.304
RMSE in R (mm/hr)	10.790	6.772	0.130	0.187	1.339	0.076	0.063	0.016	0.136	0.364	67.408	1.519
MAE in R (mm/hr)	12.231	6.010	2.823	0.181	1.336	0.081	0.059	0.030	0.133	0.681	66.839	1.508
BIAS in R (mm/hr)	16.597	8.888	-4.532	0.207	1.368	0.092	0.074	0.000	0.148	0.000	66.851	1.546
MRE in R (mm/hr)	16.629	8.766	3.842	0.174	1.288	0.100	0.072	0.024	0.128	0.542	69.890	1.458

The plot of MAE and MRE in rain-rate against time was assessed also at each optimization run and the results are shown in Figure 15. A cost function which reduced MAE and MRE at all rain-rate was sought for. Using Figure 15 together with Table 4 bias in reflectivity, bias in rain-rate, MRE in reflectivity, and mean relative error in rain-rate estimate coefficients *a* and *b* at very low accuracy (large relative error and absolute error). RMSE in either reflectivity or rain-rate give similar accuracy when used and the same applies for MAE in rain-rate and in reflectivity as cost functions. In Table 4 the difference between using RMSE and MAE was not very clear but when Figure 15 it became clear that the use of MAE give higher absolute and relative errors than when RMSE is used.

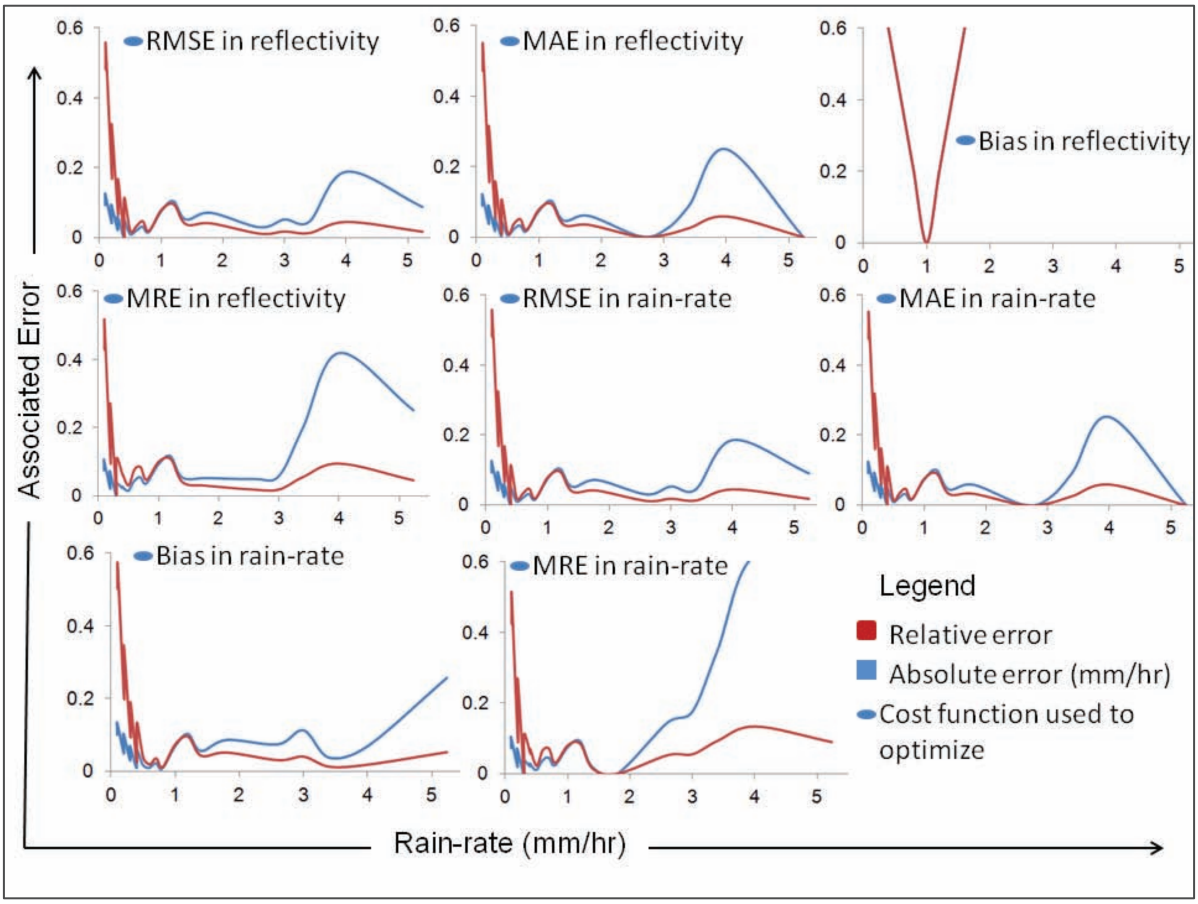


Figure 15: Curve fitting by lowering errors with respect to reflectivity and rain-rate

The same process as explained above was repeated with as constraint that the bias in reflectivity should be close to zero (0.000001 mm^6/m^3). While this condition was held constant the other cost functions were used one at a time noting the obtained residuals as done above. As shown in Table 5 similar accuracy and coefficients *a* and *b* were obtained when using any of RMSE in reflectivity or RMSE in rain-rate. MRE in reflectivity gave the same result, accuracy and parameters as the MRE in rain-rate.

Table 5: Curve fitting by optimization with constraint that bias in reflectivity should be close to zero (0.000001)

Optimizing Cost Function ↓	RMSE in *Z*	MAE in *Z*	BIAS in *Z*	MRE in *Z*	RMSF	RMSE in *R*	MAE in *R*	BIAS in *R*	MRE in *R*	Cumulative Rainfall Difference	*a*	*b*
RMSE in Z (mm6/m3)	10.792	6.823	0.000	0.186	1.336	0.076	0.063	0.014	0.135	0.327	67.678	1.516
MAE in Z (mm^6/m^3)	11.183	6.777	0.000	0.196	1.363	0.077	0.063	0.021	0.142	0.493	65.883	1.541
MRE in Z (mm^6/m^3)	12.032	7.204	0.000	0.179	1.291	0.082	0.065	0.020	0.130	0.049	70.973	1.471
RMSF	22.682	14.138	0.000	0.221	1.226	0.148	0.112	0.024	0.163	-0.553	80.220	1.351
RMSE in R (mm/hour)	10.795	6.813	0.000	0.187	1.338	0.076	0.063	0.015	0.136	0.343	67.509	1.518
MAE in R (mm/hour)	10.795	6.813	0.000	0.187	1.338	0.076	0.063	0.015	0.136	0.343	67.509	1.518
BIAS (mm/hour)	12.506	7.647	0.000	0.179	1.283	0.085	0.068	0.000	0.130	0.000	71.597	1.462
MRE in R (mm/hour)	12.032	7.204	0.000	0.179	1.291	0.082	0.065	0.020	0.130	0.049	70.973	1.471

High accuracy in the presence of a constraint in the bias in reflectivity was observed when MRE (in either reflectivity or rain-rate) and RMSE (in either reflectivity or rain-rate) were used (Table 4). The constraint removed the dilemma of selecting root mean square error or mean absolute error as a cost function. Although based in Table 5, MRE gave high accuracy when there is a constraint, further analysis using Figure 16 showed high absolute errors in rain-rate associated with the use of MRE.

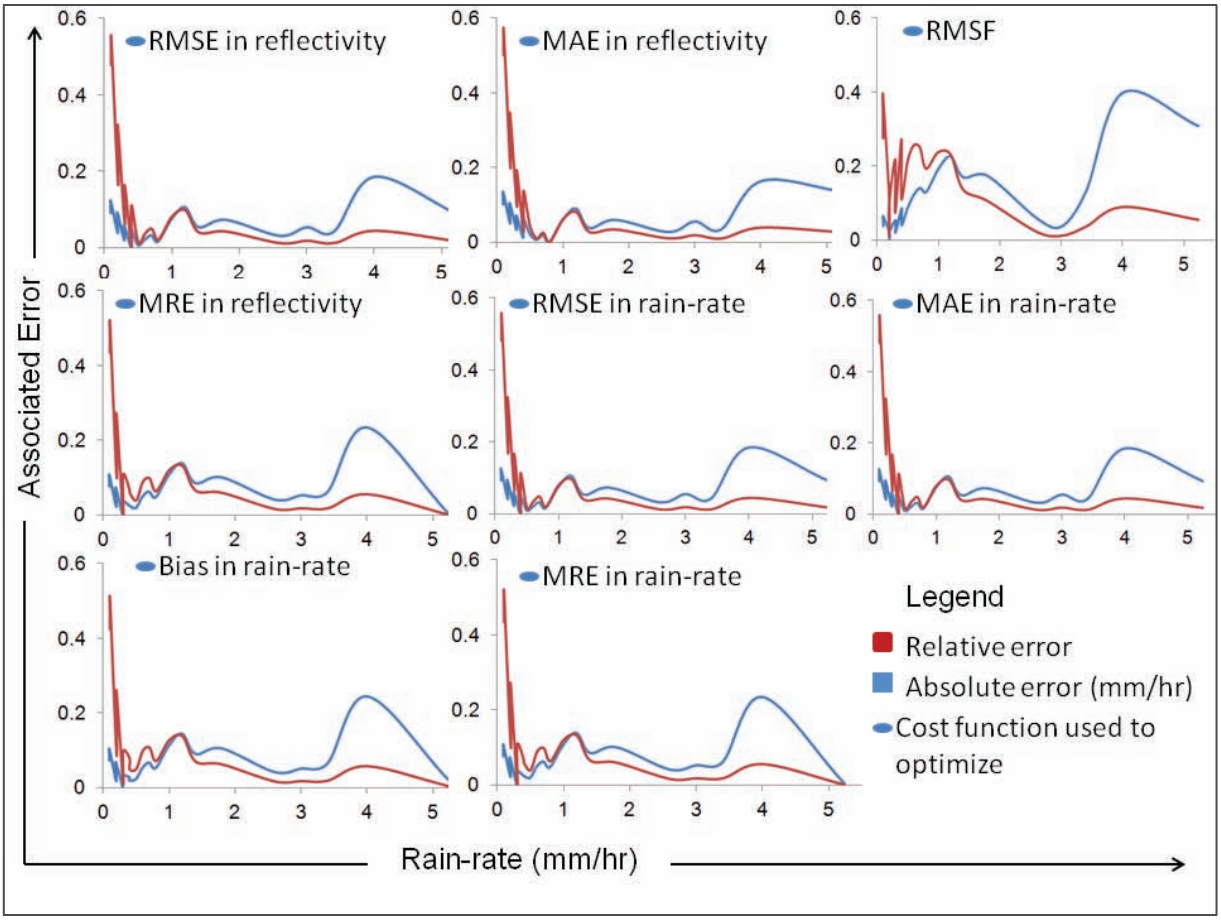


Figure 16: Curve fitting by lowering errors with respect to rain-rate with constraint that bias in reflectivity should be close to zero (0.000001)

When comparing results obtained in the presence of a constraint with when there was no constraint, it was concluded that using the root mean square error (in reflectivity or rain-rate) with a constraint to keep bias in reflectivity very close to zero yields coefficients a and b of the Z-R relationship at a higher accuracy than when other cost functions. **Therefore, in this study the data was fitted to the *Z-R* by minimizing the RMSE in rain-rate with a constraint to keep bias in reflectivity close to zero.**

8.4.2. Setting the thresholds of Reflectivity and rain-rate

The Z-R relationship obtained is dependent on the thresholds of minimum reflectivity Z_0 and minimum rain-rate R_0 used because the thresholds determine the range of values reflectivity and rain-rate for which the relationship can work (Atlas*, et al.*, 1990; Krajewski., 1991; Rosenfeld*, et al.*, 1994; Rosenfeld*, et al.*, 1993). The radar does not detect all rain-rate but there is a minimum of reflectivity and rain-rate above which the radar becomes sensitive. The steps for obtaining the thresholds are

I. A guess of the thresholds is made
II. Pairs of reflectivity and rain-rate are obtained from cumulative density function matching with the thresholds used as lower bounds of equation 14.
III. The Z-R relationship *f(Z)* if determined using the *Z-R* pairs obtained in step ii and this is used to calculate additional volume due to changing the threshold from Z_0 to Z_{0+1} expressed as

$$\Delta R_v = \int_{Z_0}^{Z_{o+1}} f(Z)P(Z)dZ - \int_{R_0}^{R_{o+1}} RP(R)dR \quad (14)$$

Where the right hand side of the equation is the difference between the rainfall estimated using the *Z*-R relationship on reflectivity values from Z_0 to Z_{0+1} by the radar and that measured by the gauge in the from R_0 to R_{0+1}.

A value of zero implies that the radar is detecting all the rainfall measured by the gauges and the best thresholds have been used. Negative values imply that the radar is not sensitive to the minimum rain-rate threshold used and the steps above should be repeated maintaining the threshold of reflectivity but increasing that in rain-rate. A positive value implies that the rainfall from the radar exceeds that from the gauges due to inclusion of non-raining pixels and the (Rosenfeld*, et al.*, 1993). In this case the steps above are repeated maintaining threshold in rain-rate but varying that in reflectivity iteratively until the additional volume (equation 14) becomes close to zero.

In this study the determination of thresholds was done iteratively using finite differences (Rosenfeld*, et al.*, 1993) as:

$$\Delta R_V = \frac{\sum_{Z_0}^{Z_r} f(Z_i) n_{Z_i}}{\sum_{Z_0}^{\infty} n_{Z_i}} - \frac{\sum_{R_0}^{R_r} R_i n_{R_i}}{\sum_{R_0}^{\infty} n_{R_i}} \quad (21)$$

Where n_{Z_i} is the number of radar observations with reflectivity Z_i and n_{R_i} is the number of gauge measurements of with intensity R_i. The threshold for reflectivity Z_0 was varied until ΔR_V was close to zero.

The additional rain volumes (Table 6) were, therefore, calculated iteratively for different thresholds of reflectivity while the threshold for the rain-rate was held at 0.1 mm/hr. R_0 was fixed because for all Z_0 the additional volume in rainfall was positive when the threshold in reflectivity was changed from Z_{0+1} to Z_0. After all the iterations the value of the additional rain volume remained positive and could any closer to zero than 0.06.

Table 6: Additional rain volume due to use of different thresholds for reflectivity and rain-rate

Z_0 (dB)	Z_r (dB)	*a* when threshold= Z_0	*b* when threshold= Z_0	ΔR_V (mm/hr)
7	8	67.509	1.518	0.060
8	9	77.528	1.452	0.064
9	10	89.129	1.397	0.060
10	11	99.265	1.380	0.069
11	12	110.623	1.379	0.065
12	13	126.282	1.345	0.067
13	14	147.750	1.242	0.062

A reflectivity value of 9 dB was finally selected as the matching threshold for the rain-rate threshold of 0.1 mm/hr because around that value the coefficients *b* appeared stabled which could be the actual value representative for the study area although the coefficient *a* still varied. These thresholds were then used for all the calibrations. It is also important to note that the *Z-R* relationships obtained differed depending on the thresholds used (Atlas*, et al.*, 1990; Krajewski., 1991; Rosenfeld*, et al.*, 1993). The method assumes that above the threshold reflectivity, both reflectivity and rain-rate increase monotonically with each other as explained by Rosenfeld et al., (1993).

8.4.3. The determination of the *Z-R* relationship

Data for the period from 2006 to 2010 from 9 locations were used for the whole study because according to Alfieri, et al., stable *Z-R* relationships are obtained when large sets of *Z-R* data are used for calibration. Data from Losser, Wierdenseveld and Almelo were not used for calibration but were rather set aside for validation. The justification for setting aside only 3 locations for validation was that according to Rosenfeld, et al., (1993) the climatological *Z-R* relationship should apply to any place provided it lies within the same climatic regime for which the relationship was developed. This was also done to ensure independence between the calibration and validation data set.

The *Z-R* relationship is affected by rainfall type (Rosenfeld*, et al.*, 1993; Steiner*, et al.*, 1995), distance from the radar which is also referred to as range (Atlas*, et al.*, 1990; Rosenfeld*, et al.*, 1993), and time (Alfieri*, et al.*, 2010; Atlas*, et al.*, 1990). In this study dependency of the *Z-R* relationship on time was mostly considered. Three calibration types which include the bulk, the seasonal and the yearly calibrations were done. In other studies bulk referred to *Z-R* relationship which applies to all rainfall types but in this study bulk refers to *Z-R* which applies regardless of year or season (time independent). The yearly calibration was done for each year between 2006 and 2010 while the seasonal calibration was done for summer, autumn winter and spring.

A reflectivity threshold of 9 dB was matched with a rain-rate threshold of 0.1 mm/hr. According to Rosenfeld, et al., (1994) each *Z-R* relationship should specify the conditions in which it was established and the time step used and in this study hourly data *Z-R* pairs were used. The procedure did not fit the *Z-R* pairs based on the exact time of their occurrence but used the raw *Z* and *R* pairs to construct cumulative distribution function (see section 6.1 and Figure 13 on probability matching). *Z* and *R* where matched corresponding to the i-th percentile for i=0, 5, 10, 15, -----, 90, 95, 96, 97, 98, and 99%. Atlas et al., (1990) used i=10, 20, --- and 90 %.

The pairs of reflectivity and rain-rate obtained from matching percentiles of cumulative density functions of reflectivity and rain-rate were used to obtain *Z-R* relationships. This was done through an optimization process as explained in Chapter 6 by minimizing the root RMSE as explained in section 8.4.2. The results obtained in each calibration are discussed below.

8.4.4. Results of the bulk and seasonal *Z-R* relationships

Results in Table 7 show that the reflectivity and rain-rate pairs obtained by matching cumulative density function of *Z* and *R* fitted to the power laws at low values of RMSE, MAE and MRE. The RMSF values close to 1 for all calibration types done as required. The *Z-R* relationships displayed seasonal variations with coefficient *b* being higher for autumn and spring than for summer and winter. A study by Atlas, *et al.*, (1990) in Germany showed that *Z-R* relationships vary with seasons and this agrees with findings of this study (Table 3). They lower values of *b* in winter and spring than in summer and autumn while in this study lower values of *b* were in winter and summer than in autumn and spring. This was attributed to differences in climatology and other localized effects between the two places which can cause differences in rainfall trends observed.

Table 8 show that large variations were observed in coefficient *a* which ranged between 75 and 105 than in b which only ranged between 1.2 and 1.7 across the seasons. The highest value of coefficient *a* (103.2) was observed in autumn. According to Shelton (2009) the coefficient *a* usually ranges between 0 and 500 while coefficient *b* ranges mostly between 1 and 2 and the values obtained in this study agree with this. However, values of coefficient *b* greater than 2 are also possible (see Table 3) although in this study the values obtained did not reach that high. The bulk *Z-R* relationship obtained was different from the ones found in literature (Table 3) for other places showing that *Z-R* relationships need to be calibrated using gauges for each place since they vary from place to place and also from time to time.

Table 7: The bulk and seasonal *Z-R* relationships for the Regge and Dinkel district

	Summer	Autumn	Winter	Spring	Bulk (All times)
a	87.565	103.193	77.162	81.956	89.129
b	1.334	1.693	1.237	1.591	1.397
RMSE in reflectivity (mm^6/m^3)	25.303	24.122	6.807	26.429	8.172
MAE in reflectivity (mm^6/m^3)	15.765	16.683	4.711	15.028	6.789
Bias in reflectivity (mm^6/m^3)	0.000	0.000	0.000	0.000	0.000
MRE in reflectivity (mm^6/m^3)	0.176	0.285	0.138	0.261	0.189
Root Mean Square Factor (RMSF)	1.126	1.476	1.279	1.532	1.348
RMSE in rain-rate (mm/hr)	0.143	0.113	0.065	0.132	0.071
MAE in rain-rate (mm/hr)	0.106	0.100	0.051	0.104	0.061
Bias in rain-rate (mm/hr)	0.002	0.028	0.008	0.035	0.013
MRE in rain-rate (mm/hr)	0.136	0.194	0.116	0.190	0.145

8.4.5. The results of the annual *Z-R* calibration and the associated accuracy

Table 8 shows that the *Z-R* relationships were not the same for different years. As an example for 2006 a *Z-R* relationship $Z=114.455R^{1.321}$ was obtained while it was $Z=70.821R^{1.550}$ for 2007.Alfieri, *et al.*, (2010) did a work in which the *Z-R* relationship was continuously adjusted with time implying that he acknowledged that it varies significantly with time which agrees with the findings of this work. In their work the *Z-R* relationship was recalibrated in every time step using pairs of reflectivity and rain-rate from the previous moment to establish a *Z-R* relationship for the next moment. However, the variations in parameter *a* were larger than in *b*.

Table 8: Accuracy of the fit to the Z-R relationship for the year 2006

	2006	2007	2008	2009	2010
a	114.455	70.821	78.060	84.105	95.649
b	1.321	1.550	1.782	1.504	1.125
RMSE in reflectivity (mm^6/m^3)	6.905	35.962	43.060	19.626	27.431
MAE in reflectivity (mm^6/m^3)	5.237	22.905	28.871	13.907	18.337
Bias in reflectivity (mm^6/m^3)	0.000	0.000	0.000	0.000	0.000
MRE in reflectivity (mm^6/m^3)	0.139	0.347	0.359	0.240	0.225
Root Mean Square Factor (RMSF)	1.237	1.590	1.676	1.426	1.245
RMSE in rain-rate (mm/hr)	0.047	0.212	0.174	0.112	0.219
MAE in rain-rate (mm/hr)	0.039	0.177	0.161	0.100	0.157
Bias in rain-rate (mm/hr)	0.004	0.049	0.052	0.013	0.009
MRE in rain-rate (mm/hr)	0.110	0.252	0.256	0.175	0.198

According to Wilson (1979), low values of coefficient *b* and large values of coefficient *a* imply increased convective activities. Based on this we can deduce that for the bulk calibration, summer and winter, the rainfall type could have mostly been convective due to low values of coefficient *b* observed as shown in Table 7. The same applied for the years 2006 and 2010 which also had low values of coefficient *b* 1.321 and 1.125, respectively. High values of coefficient *b* observed in autumn spring, 2007, 2008 and 2009 could then imply that less convective activities could have been recorded during these periods. The overall deduction from this could be that rainfall types over the Regge and Dinkel could vary over time with seasons and years.

Figure 18 shows how coefficient *b* changed in response to the changes which occurred over the length of the study period to coefficient *a*. Regression analysis (Appendix 1) shows a decrease in coefficient *b* as coefficient *a* was increasing (r-squared value of 0.4347).

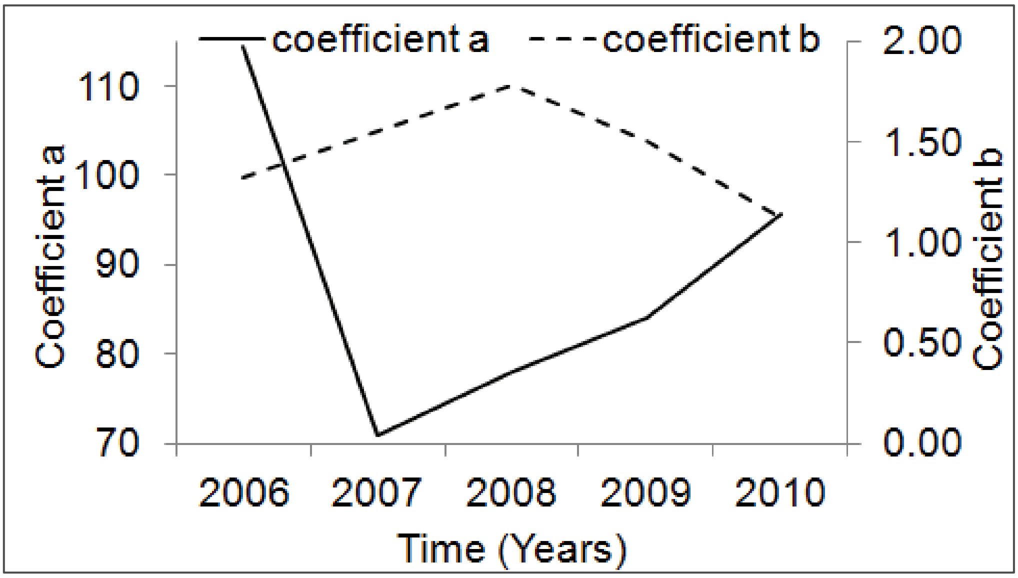


Figure 17: Trends in coefficients *a* and *b* of the *Z-R* relationship

The *Z-R* relationships obtained in all the calibrations shown in Table 7 and Table 8 were different from the Marshall and Palmer *Z-R* relationship. This explains the importance of calibrating for each climatic regime instead of using a fixed theoretical relationship in all places.

8.4.6. Comparison of coefficients with values found in Germany and Netherlands in previous studies

Wessels (1972) used the reflectivity data from the radar at De Bilt together with drop size distribution data measured from rain drops at the ground. Value of 259 for coefficient *a* and of 1.5 for coefficient *b* were obtained. Atlas et al., (1990) established the *Z-R* relationship in the neighbouring Germany for different seasons and the results are in Table which also show values of coefficient *a* greater than 200. Compared with these previous studies done in the Netherlands and the Germany case, the values of coefficient *a* were smaller than expected although they were also expected to differ for different places. Values of coefficient *b* were within the range of those found in these studies but also unique for the Regge and Dinkel.

9. VALIDATION

This section assesses the accuracy of the proposed *Z-R* relationships compared with that of the Marshall and Palmer *Z-R* relationships. The idea is to identify the better of the two and how well they work for the Regge and Dinkel when compared with the gauges. The following steps were taken during the validation process;

- Validation of the probability matching method
- Validation for point measurements
- Validation of the calibration process

The reflectivity and rain-rate data from Wierdenseveld , Almelo and Losser were set aside for this purpose to allow independence from the calibration set of data. Each of the steps is described in detail below.

9.1. Validation of the probability matching method

In order to assess the accuracy of the calibration process, cumulative density functions of rainfall constructed using the proposed *Z-R* relationships for each calibration type and also using the Marshall and Palmer *Z-R* relationship. The cumulative density functions obtained were compared with the ones determined using in situ data for the same period. In principle the cumulative density functions constructed using the climatological *Z-R* relationship should match with those from the gauge provided the in situ data is from the same climate regime for which the *Z-R* relationship was established. This was done using non-zero *Z-R* pairs and accuracy was assessed using the RMSE, MAE and RMSF. Water depth was also calculated from the cumulative density functions and the results are presented in Table 9.

Table 9: Accuracy of the proposed Z-R relation by comparing cumulative density function in rain-rate

Calibration	Proposed *Z-R*			Marshall and Palmer *Z-R*		
	RMSE (mm)	MAE (mm)	RMSF	RMSE (mm)	MAE (mm)	RMSF
Bulk	0.117	0.079	1.395	0.674	0.356	1.596
Winter	0.085	0.052	1.320	0.630	0.335	1.652
Spring	0.152	0.115	1.588	0.565	0.349	1.595
Summer	0.252	0.109	1.329	1.072	0.544	1.683
Autumn	0.121	0.102	1.583	0.344	0.234	1.478
2006	0.249	0.066	1.267	0.595	0.236	1.429
2007	0.255	0.120	1.459	0.614	0.356	1.633
2008	0.316	0.157	1.710	0.682	0.380	1.626
2009	0.189	0.107	1.482	0.629	0.367	1.677
2010	0.183	0.111	1.245	0.868	0.387	1.601

The results in Table 9 show that the probability matching process was accurately done because the cumulative density functions constructed using the proposed *Z-R* relationships and an independent validation data set fitted to those obtained from the gauges at low RMSE and MAE and at RMSF close to 1. The accuracy of the fit was higher using the *Z-R* relationships obtained from probability matching than using the Marshall and Palmer *Z-R*. As an example, using the proposed bulk *Z-R* relationship RMSE was 0.117 while it was 0.674 when using the Marshall and Palmer. The water depths (cumulative rainfall) obtained using the proposed *Z-R* relationships were closer to those obtained using in situ measurements than were those obtained using the Marshall and Palmer *Z-R* relationships. The proposed bulk *Z-R* relationship, for example, gave cumulative rainfall amount of 2962.1 and the Marshall and Palmer gave 1741.0 while the value was 2965.4 based on gauge measurements. This implies that the probability matching method produced *Z-R* relationships which should be more accurate in estimating point and cumulative rainfall than the Marshall and Palmer *Z-R* relationships.

Table 10: Comparison of cumulative amounts of radar derived rainfall estimates with gauge measurements

	Cumulative rainfall		
	Gauge (mm)	Proposed *Z-R* (mm)	Marshall and Palmer *Z-R*
Bulk	2965.4	2962.1	1741.0
Winter	797.9	806.7	445.0
Spring	458.3	485.7	277.7
Summer	983.8	973.5	520.2
Autumn	836.1	876.6	578.5
2006	303.5	293.0	208.5
2007	692.5	783.6	393.0
2008	774.1	805.4	464.6
2009	495.1	486.3	281.0
2010	700.2	682.1	393.9

9.2. Validation for point measurements

The same non-zero reflectivity and rain-rate data used in section 9.1 were also used for validation for point rainfall estimation. The difference is now that in section 9.1 collocation and synchronization were not considered as *Z* and *R* were organized in ascending order such that minimum *Z* was matched with minimum *R* and the procedure assumed that *Z* and *R* were increasing monotonically with each other. In this step collocation and observation time were considered because in real time sense, reflectivity and rain-rate should coincide. Hourly reflectivity and rain-rate were, therefore, matched considering where and when they were measured. Rainfall amounts were also calculated using the proposed *Z-R* relationships and the Marshall Palmer *Z-R* relationship. The rainfall amounts obtained using *Z-R* relationships were compared with those from in-situ measurement and the results are shown in Table 11.

Although section 9.1 showed that the calibration process was accurate, the proposed *Z-R* relationships give higher error on point hourly rainfall estimates. Although the rainfall depths obtained were similar to those obtained in section 9.1, the proposed *Z-R* relationships were no longer giving higher accuracy than the Marshall and Palmer. They were giving higher RMSE and MAE than when estimations are done using the Marshall and Palmer *Z-R* relationship. The proposed *Z-R* relationships were over-estimating point rain-rate more than the Marshall and Palmer was under-estimating it. This was because the proposed *Z-R* relationships have mostly low values of coefficients *a* and *b* (see Table 7 and Table 8) than the Marshall and Palmer *Z-R* such that for a particular reflectivity they give higher rain-rate than the latter and this together with low correlation has resulted in the high errors.

Table 11: Accuracy of the proposed *Z-R* relation on point hourly rainfall estimation

Calibration	Proposed *Z-R*		Marshall and Palmer *Z-R*	
	RMSE (mm)	MAE (mm)	RMSE (mm)	MAE (mm)
Bulk	1.192	0.206	1.034	0.198
Winter	0.735	0.163	0.588	0.159
Spring	0.309	0.107	0.307	0.106
Summer	1.399	0.204	1.083	0.199
Autumn	0.526	0.142	0.535	0.142
2006	0.744	0.147	0.658	0.145
2007	0.744	0.180	0.732	0.180
2008	0.702	0.147	0.786	0.149
2009	0.686	0.154	0.663	0.153
2010	0.921	0.147	0.672	0.142

The reason for high errors in point hourly measurements occurred because the rain-rate was not increasing with reflectivity as was expected. There was a mismatch in tendency between coinciding reflectivity and rain-rate measurements such that any reflectivity was matching with any rain-rate thus disobeying the principle. If rain-rate was increasing with reflectivity the proposed *Z-R* relationships were going to be more accurate than the Marshall and Palmer *Z-R* relationship as shown in section 9.1 when the same data was arranged in ascending order. The implication of this is that the radar was not detecting rain-rate in the accurate sense. In real time sense reflectivity values were not matching with rain-rate while the *Z-R* relationships assume otherwise.

9.3. Time series analysis

A comparison was done of the monthly rainfall amounts determined from in situ data with those obtained from the radar estimations of rainfall. In order to avoid associated errors, data for periods corresponding with missing images was not used. Any day with six or more consecutive radar reflectivity images missing was not included in the accumulations. The rainfall for the rest of the days were accumulated into monthly amounts in order to see the cumulative impact of errors shown in section 9.2 on rainfall estimates. This was done for each calibration type in comparison also with the Marshall and Palmer *Z-R* relationship.

The proposed bulk and the Marshall and Palmer *Z-R* relationships were applied on data for the year 2006 to give the results in Figure 19 for each place and for the average of the three places. The radar could not detect most of the rainfall events resulting in under-estimation of monthly rainfall as was not expected after the calibration. The high errors in hourly measurements are accumulating over the month resulting in a deceiving result which appears as if the proposed *Z-R* gives better estimates than the Marshall and Palmer *Z-R*. The three validation locations were all affected in a similar implying there could be a constant factor affecting all the locations.

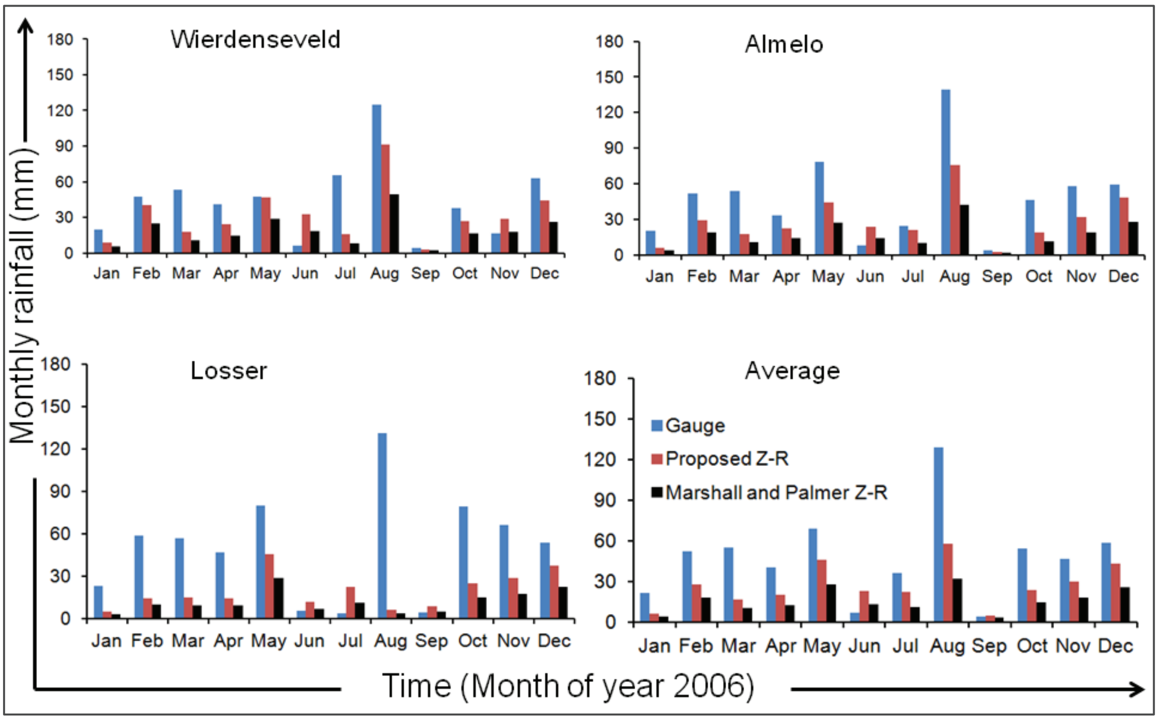


Figure 18: Monthly rainfall obtained using the bulk *Z-R* relationship

Figure 20 is based on monthly rainfall obtained from accumulating hourly measurements of rainfall with radar based estimated for each month calculated using the proposed *Z-R* relationship for the season in which the month is found.

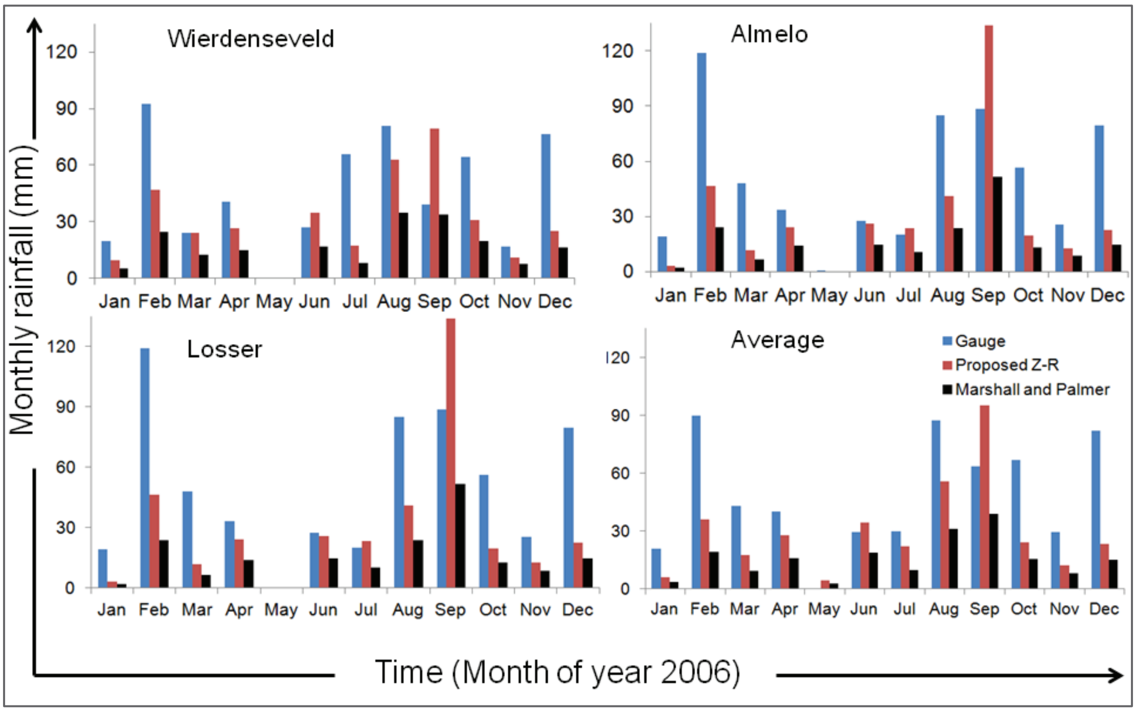


Figure 19: Monthly rainfall obtained using the seasonal *Z-R* relationships

Similar to the bulk *Z-R* relation, proposed seasonal *Z-R* relationships and the Marshall and Palmer *Z-R* relationship were under-estimating the monthly rainfall (Figure 20). Due to large values of coefficients *a* and *b* the Marshall Palmer gave lower values of monthly rainfall the proposed seasonal *Z-R* relationships (Figure 20) but both were associated with errors shown in section 9.1

Monthly rainfall amounts were similarly calculated for each year in order to assess the performance of the proposed yearly *Z-R* relationships found in this study. The monthly rainfalls obtained using the *Z-R* relationship for each calibrated year showed the similar result that the radar was missing rainfall events resulting in under-estimations (Figure 21). Not only hourly rainfall amounts but also errors in them being over time could be accumulated to come up with these monthly figures that become, therefore, unreliable.

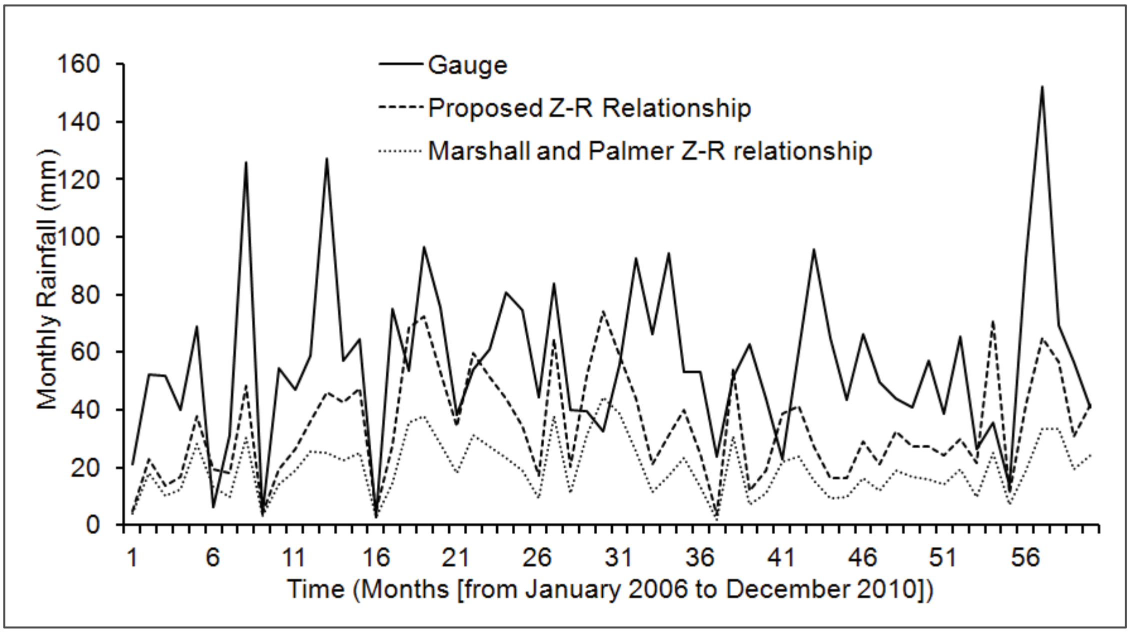


Figure 20: Monthly rainfall obtained using the proposed yearly *Z-R* relationship

Therefore, the time series analysis gives the picture of how all the calibrated *Z-R* relationships affect rainfall estimation as will be highlighted in the discussion which follows.

9.4. The effect of missing images

In the analysis above (section 9.1 through to 9.3) the volumes of rainfall obtained were calculated only from days where data were available. The days with missing data were noted such that the difference in rain volumes between that estimated using radars and that observed using gauges was not attributed to missing data. Figure 22 shows the propagation of this difference and number of missing images with time (Note that a month with 30 days had 8610 five-minute images).

The difference between monthly rainfall measured by gauges and estimated by radar did not show any strong relationship with the amount of missing data. This is because the volume of rainfall corresponding with the missing data was not used in any computation and was accounted for. A regression analysis in Appendix 2 showed very low correlation between the missing images and the under-estimation of rainfall by radar.

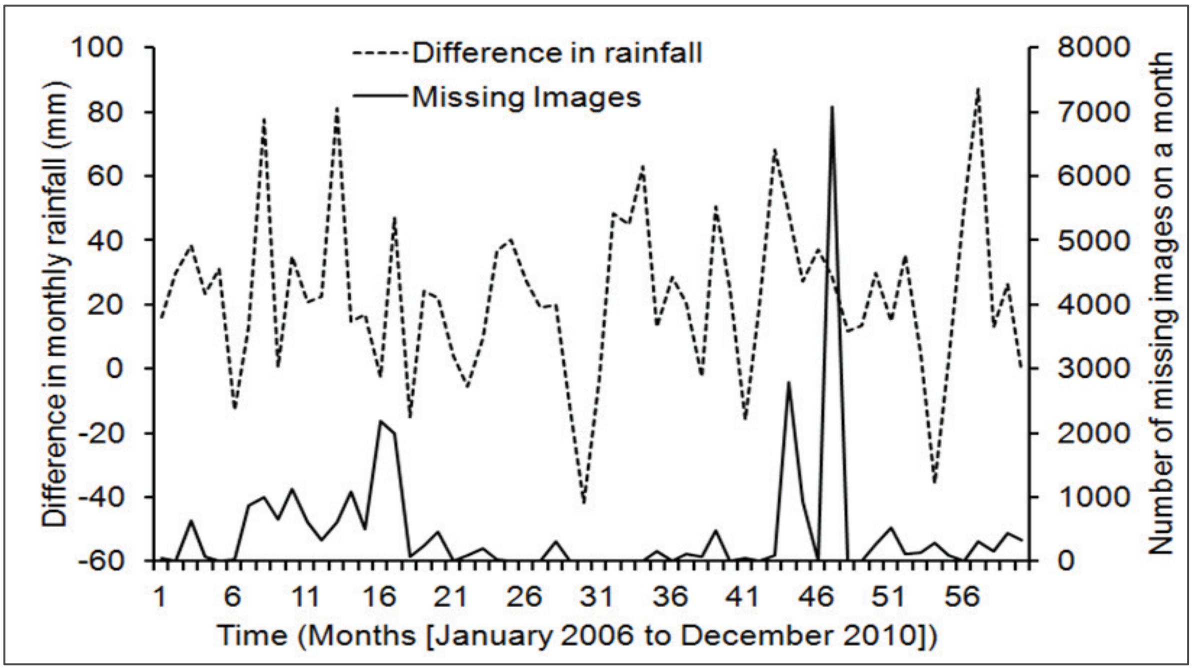


Figure 21: Effect of missing data on under-estimations by the radar

Therefore, the difference between rainfall amounts measured by the gauges and that estimated by the radars could not be clearly attributed to the effect of missing radar images. Using Figure 21to explain this, we can take month 34 as an example where there were no missing images but the difference was higher than that seen in month 47 where there were about 7000 missing images.

9.5. Bias correction

Bias was defined using equation 8 as the mean of the differences between estimated and observed rainfall while accurate estimations require that there should be no bias in rainfall accumulations (Alfieri*, et al.*, 2010; Holleman, 2006). In order to correct for bias in accumulations a bias correction factor is applied on the radar accumulations. This bias correction factor (*F*) is defined as the mean of the ratios of the cumulative estimated rainfall to the cumulative rainfall from in situ measurements (Holleman, 2006; Rosenfeld*, et al.*, 1993; Wilson & Brandes, 1979). Using a network of in-situ measurements and radar based estimates the bias is expressed as

$$F = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{G_i}{R_i}\right) \qquad (22)$$

Where *G* is the estimates from radar and *R* represents estimates from gauges (Rosenfeld*, et al.*, 1993; Wilson & Brandes, 1979). The closer the bias correction factor is to 1 the higher the accuracy of the rainfall estimates for large spatial and time step. In this study *F* was calculated using data from the three validation locations

The condition of the window probability matching method is that there should be at most very low bias in rainfall estimates based on the *Z-R* relationships obtained (Rosenfeld*, et al.*, 1993). The calibration using local gauges should reduce bias and increase accuracy relative to the theoretical Marshall and Palmer and this was the case in other studies (Alfieri*, et al.*, 2010; Mapiam, 2008). However, this was not the case for the Regge and Dinkel district since the radar based rainfall estimates were under-estimating real time rainfall accumulations as was shown in sections 9.3 and 9.4 and also due to errors discussed in section 9.2. The differences in accumulated rainfall discussed in section 9.3 were quantified in this section. In order to show that there was still bias after the application of the window probability matching method, the cumulative rainfall amounts and the biases associated with each calibration type were calculated and results are shown in Table 12.

Analysis of bias based on the bulk and seasonal *Z-R* was done for the year 2006 and that of yearly was done applying yearly *Z-R* relationships for all years for the period from 2006 to 2010. Average daily rainfall of the three validation locations was used.

Table 12: Comparison of radar based cumulative rainfall estimates with values based on in-situ data.

Calibration Type	Cumulative rainfall based on gauges (mm)	Proposed *Z-R*		Marshall and Palmer *Z-R*	
		Cumulative rainfall (mm)	Bias correction factor, F	Cumulative rainfall (mm)	Bias correction factor, F
Bulk	588.5	324.0	0.55	191.2	0.32
Seasonal	593.7	331.9	0.56	190.6	0.32
Yearly	3428.0	2074.0	0.61	1185.6	0.35

The use of proposed *Z-R* relationships resulted in under-estimation of cumulative rainfall amounts by at least 39% (Table 12). The Marshall and Palmer *Z-R* relationship resulted in larger under-estimations than the proposed *Z-R* relationships. The closed the *F* was to 1 was when it took a value of 0.61 using the yearly *Z-R* relationships implying that the accuracy of radar estimates did not improve.

In order to confirm the bias, the correction factors in Table 12 were applied based on the definition of bias in the following manner:

$$(Cumulative\ daily)_{corrected} = F * (Day\ of\ year) + (Cumulative\ rainfall)_{before\ correction} \quad (23)$$

Figure 22 shows that the difference between in-situ and radar based rainfall estimates was reduced after bias correction implying that the window probability matching method could not adequately remove the bias in rainfall estimates for the Regge and Dinkel. The bias could be due to the effect of the long distance between the radar and the study area. The range can make signal detected by the radar to be weak and not representative of rainfall intensities measured on the ground.

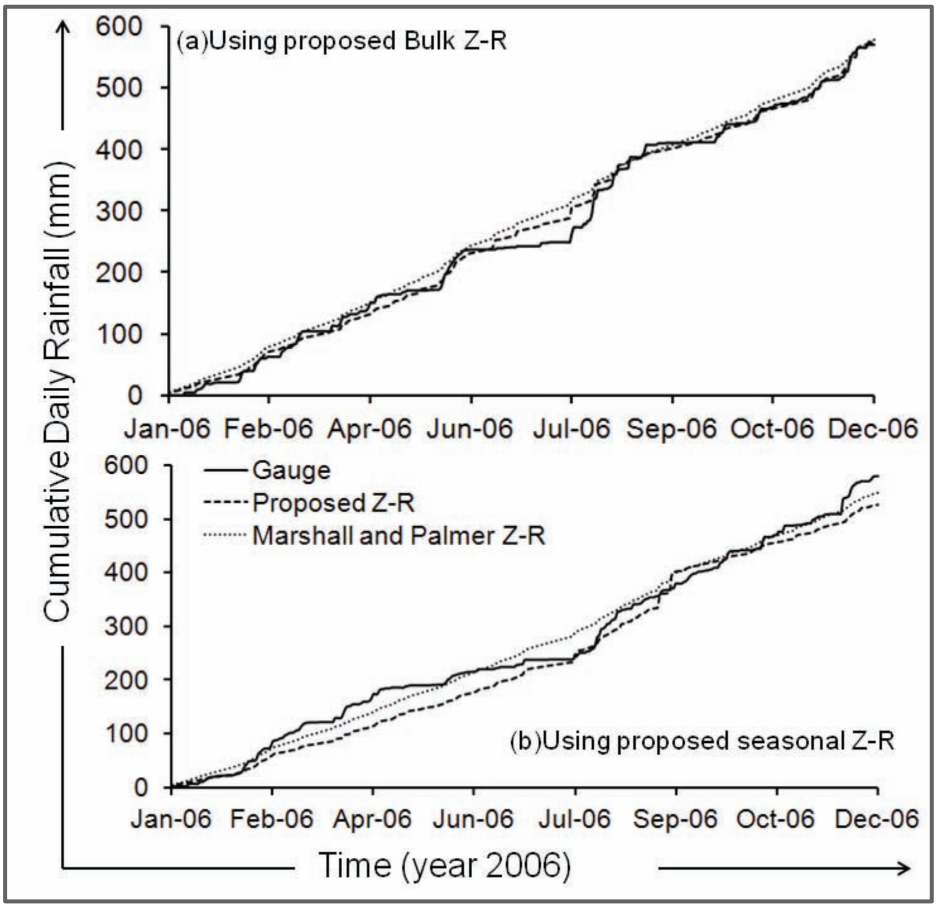


Figure 22: The bias corrected cumulative rainfall curves

The biases and errors found in this study can be associated with the effect of long distance from the radar of the Regge and Dinkel district. At long ranges the radar is likely to sample different hydrometeors due to beam overshooting resulting in under-estimation of rainfall (Hunter, 1996). Sampled volumes increase at long range leading to averaging out of small but intense events because the beam will not be completely filled with precipitation (Sanchez-Diezma *et al.*, 2000; Wilson & Brandes, 1979). This range degradation (Holleman, 2006; Kitchen & Jackson, 1993; Meischner *et al.*, 1997; Neyman, 1996; Sanchez-Diezma, *et al.*, 2000; Smith *et al.*, 1996) has caused under-estimation of rain volumes and unreliability of the radar rainfall estimates over the Regge and Dinkel district. Biggs and Atkinson (2011) have also shown that accuracy of radar rainfall estimated and their correlation with gauges decrease with increasing range which could agree also with the assumed causes of the under-estimations discussed.

10. CONCLUSION AND RECOMMENDATIONS

A large number of *Z-R* relationships can be found in literature and among the causes of this is the variation in the predominance of rainfall types across the world. Calibration of radar rainfall estimates using in-situ measurements by gauges has been used with success to reduce bias between these two different techniques of quantifying rainfall received by an area (Wilson & Brandes, 1979). The motivation of this study was, therefore, based on the limitations of using a fixed *Z-R* relationship across the entire Netherlands, which ignores variability in rainfall types and other factors. This approach was, therefore, deemed to be associated with errors that could be resolved by calibration using measurements from local gauges. The focus was on improving accuracy of radar based rainfall estimates for the Regge and Dinkel districts in the eastern part of the Netherlands. Calibration was done using the window probability matching method because the method avoids errors in calibration associated with collocation and synchronization of radar and rain gauge measurements (Rosenfeld*, et al.*, 1994). The relationships between radar reflectivity and rain-rate (*Z-R* relationships) adjusted to the climatology of the Regge and Dinkel district were obtained based on reflectivity data from KNMI and rainfall data from the Water Board Regge and Dinkel. The performance of the *Z-R* relationships obtained was compared with that of the Marshall and Palmer *Z-R* relationship. The Marshall and Palmer *Z-R* relationship is currently used by KNMI over the entire Netherlands (Holleman, 2006). The findings of this study are highlighted below.

10.1. In situ measurement analysis

- The rainfall amounts received over the Regge and Dinkel district were mostly in the range between 700 and 900 mm/year although a minimum of 578 mm/year was recorded by the rain gauge located at Goor.
- A slight increase in mean annual rainfall north eastwards was observed over the Regge and Dinkel.
- The rainfall at Goor showed a unique decline with time over the 5 year period considered in this study and this was not the same for other locations implying that rainfall trends can also vary over time within a small catchment.

10.2. Selection of cost function for optimization

- **Optimization using the RMSE with a constraint to keep bias in reflectivity close to zero converges to a *Z-R* relationship at the best low values of other errors.**
- The bias in reflectivity cannot be used alone as a cost function to optimize because the iterations will not converge. A value for coefficient *b* of 617.1 was obtained when using bias in reflectivity and this value was beyond the acceptable range based on previous studies.
- The MAE and MRE can gave reasonable results but were not as accurate as the RMSE.
- The *Z-R* relationships obtained were sensitive to the cost function used although results from RMSE, MRE, bias and MAE were closely comparable. They all had values for *a* close to 65.0 and *b* close to 67.0. Significantly different results from these were 75.2 for *a* and 1.3 for *b* obtained when minimizing the RMSF.

10.3. Selection of reflectivity and rain-rate thresholds

- The radar does not detect all rainfall intensities. There is a minimum intensity which should be matched with minimum of reflectivity in an iterative process. The *Z-R* relationship was found to vary with value of minimum reflectivity matched with minimum rain-rate.
- A 1.0 dB difference in reflectivity threshold used resulted in marked differences between the *Z-R* relationships obtained. As an illustration to this, a *Z-R* relationship of $Z=67.51R^{1.52}$ was obtained when a reflectivity threshold of 7.0 dB was used while $Z=77.5R^{1.45}$ was obtained when the threshold was 8.0 dB.
- Selection of threshold also determines the amount of water rainfall that cannot be accounted for by the radar estimates.

10.4. The Z-R relationships for the Regge and Dinkel

- The *Z-R* relationships were obtained for the Regge and Dinkel by optimization at low values of RMSE, MAE and MRE and RMSF close to 1.0 during the calibration phase.
- The coefficients *a* and *b* of the *Z-R* relationships obtained for each calibration type were mostly smaller than those of the Marshall and Palmer *Z-R* relationship. Coefficients *a* ranged between 70.0 and 115.0 while *b* ranged between 1.1 and 1.7 and for the Marshall and Palmer currently in use by KNMI *a* is 200.0 and *b* is 1.6.
- With the exception of proposed relationships for autumn, spring and 2008, the proposed bulk *Z-R* relationship and those of the other years and seasons had values of coefficient *b* less than 1.6 currently in use. According to Wilson (1979), *b* decreases with increasing convective intensity which could imply that predominance of convective rainfall for the periods where *b* was low over the Regge and Dinkel. The other implication of the variations in the coefficients is that they change with time, seasonally and annually. Alfieri et al., (2010), even proposed real time adjustment of the *Z-R* relationships showing that they can even vary between short time interval.
- Coefficient *a* displayed higher variability than *b* over time and for different calibrations. The values obtained were in the acceptable range when compared with literature in general. However, compared with values obtained in past studies in the Netherlands using the same De Bilt radar (Wessels, 1972) and in the nearby Germany (Atlas*, et al.*, 1990), coefficients *a* were small while coefficients *b* were in the range.

10.5. Validation

Reflectivity and rainfall data coinciding with locations at Wierdenseveld, Goor and Losser were used for validation to enable independence from the calibration dataset.

10.5.1. Validation of the calibration process

- Cumulative density functions of rainfall were constructed using in-situ measurements, the each proposed *Z-R* separately and also using the Marshall and Palmer *Z-R* relation. The cumulative density functions derived from the radar estimates of rainfall were compared with those derived from in-situ measurements.
- The cumulative density functions of rainfall obtained using the probability matching method derived proposed *Z-R* relationships matched with those obtained from the in-situ data highly accurately more than those derived from the Marshall and Palmer *Z-R* relationship. As an example to this, the RMSE of the match was 0.117 mm when the proposed bulk *Z-R* relationship was used compared to 0.674 mm when the Marshall and Palmer *Z-R* relationship was used.

- The window probability matching resulted in estimations of cumulative rainfall that closely resembled cumulative rainfall amounts from the gauges. When the proposed *Z-R* relationship for spring was used, a total amount of rainfall of 458.3 mm was obtained and 277.7 mm was obtained using the Marshall and Palmer *Z-R* relationship while the total was 485.7 using in-situ measurements.
- This only applies if reflectivity is increasing with rain-rate because the method matches minimum reflectivity with minimum and requires reflectivity to increase with rain-rate above the thresholds. The findings show that the accuracy of the calibration procedure was high because the cumulative density functions and rainfall totals could still closely match when an independent dataset.

10.5.2. Estimation of point hourly measurements

- The proposed Z-R relationships were validated on **collocated and synchronous** reflectivity and rainfall measurements. When these real time measurements were considered on hourly basis, it was observed that the window probability matching method did not improve the accuracy of the estimation of these by the radar.
- The proposed *Z-R* relationships resulted in rainfall estimates which gave larger errors than those obtained with the Marshall and Palmer *Z-R* relationship. The proposed bulk *Z-R* relationship had an RMSE of 1.192 mm while the Marshall and Palmer gave and RMSE of 1.034 mm.
- The same result that the proposed *Z-R* relationships were not improving the accuracy of rainfall estimates relative to the Marshall and Palmer was observed for all calibrations types. Expectations that the method was going to improve the accuracy were, therefore not achieved. According to Rosenfeld et al., (1993), this loss of accuracy was not expected provided the *Z-R* relationship is used for a place within the climatic regime for which it was calibrated.
- Due to low values of coefficients *a* and *b* the proposed *Z-R* relationships gave higher values of rain-rate compared with the Marshall and Palmer *Z-R* relationship for the same reflectivity. This was because according to the inversion of the power law (equation 1), rain-rate decreases with the increasing of coefficients *a* and *b* for a given radar reflectivity value.
- The large errors could possibly be due to range degradation. The radar may be not sensitive to rain-rate because the Regge and Dinkel is located away from De Bilt where the radar is located and the signal could weakened as they traverse for long two way distances. This would also imply a lot of mixing at long ranges caused by beam overshooting such that intense activities are lost out due to averaging.

10.5.3. Retrieval of average hourly rainfall for the validation locations

- Retrieval of average hourly rainfall based on the three validation locations (Losser, Almelo and Wierdenseveld) using the proposed *Z-R* relationships was also not at a higher accuracy than the Marshall and Palmer for the same assumed effect of mismatch due to range degradation mentioned above.

10.5.4. Accumulated rainfall amount

- The condition of the probability matching method that there should be very small differences between measured and estimated rainfall (bias) was not met. Although the biases were lower than those of the Marshall and Palmer which could not account for between 65 % and 68 % of the rainfall, between 39 % and 44 % of the monthly events were still missed using proposed *Z-R* relationships. This implies that bias remained high even after calibration.

- The radar was under-estimating rainfall accumulations as was noted using monthly rainfall distribution analysis. The bulk *Z-R* relationship could not account for 44% of the annual rainfall for 2006, the yearly *Z-R* relationships could not account for 40% of the annual rainfall for 2006 to 2010 and the seasonal *Z-R* relationships missed 44% of the rainfall for 2006. The Marshall and Palmer even under-estimated more than the proposed *Z-R* relationships missing 68 %, 65% and 68 %, respectively, for the same periods.
- Under-estimation of rainfall was also attributed to the effect of range (Sanchez-Diezma*, et al.*, 2000; Wilson & Brandes, 1979).

10.6. Recommendations

In light of the findings of this drawn above recommendations made are as listed below.

- Data assimilation and other gap filling techniques should be used to fill missing radar reflectivity data for the sake of future researches and other applications in the Netherlands.
- Since the radar was found to be less sensitive and unreliable in the estimation of rainfall for the Regge and Dinkel district, the use of other remote sensing techniques to improve rainfall estimation was also found to be necessary.
- A research was done in Turkey in which they came up with a linear algorithm of determining radar reflectivity as function of factors which included range and altitude of the gauge (Öztürk & Yılmazer, 2007). This was used to obtain radar reflectivity corrected for the effect of these factors. A similar approach can also be done for the Regge and Dinkel and range should be one of the factors to be considered for this.
- Comparison of the performance of proposed *Z-R* relationships with existing *Z-R* relationships such as the Marshall and Palmer is important in interpreting the accuracy of the radar rainfall estimates during calibration.
- Sustenance and maintenance of the rain gauge network remains a crucial option to make rainfall data for the Regge and Dinkel accurate and reliable for use in all applications.

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