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Quality of Ground-based WeatherRadar Observationsof Rainfall over the Water Board District Regge and Dinkel of the Netherlands

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ABSTRACT

The relationships between radar reflectivity (Z) and rain-rate (R) adjusted to the climatology of the 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 entire 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 from each calibration. The variations are due to differences in rain drop size distribution and hence predominant rainfall types in space and time. However, contrary to the expectations, the Z-R relationships obtained using the window probability matching did not improve the accuracy of radar rainfall estimation. The Regge and Dinkel area is located more than 100 km away from the de Bilt radar and this causes the unreliability of the rainfall estimates from the radar (range degradation). 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 need to identify weather radar which is close to the Waterboard Regge and Dinkel district and use it to monitor rainfall for the area. This may also imply the need to install weather radar within the area to eliminate the impact of range degradation on accuracy of radar rainfall estimates.

Keywords: windowprobability-matching, rain-rate, Z-R, errors, reflectivity, calibration, Regge and Dinkel

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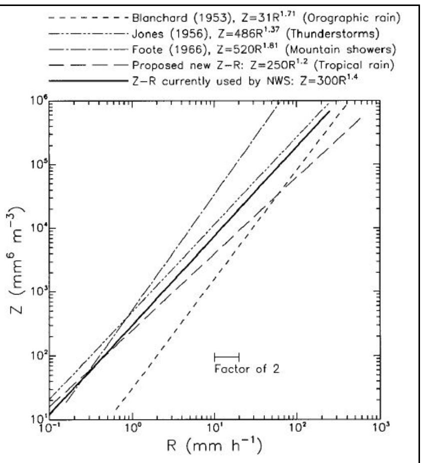
INTRODUCTION

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 (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 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.

MATERIALS AND METHODS

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:

- Quantify the spatial and temporal rainfall variability over the Regge and Dinkel area;
- Develop Z-R relationships specific for the Regge and Dinkel area;
- Identify the time dependency of the Z-R relationships (e.g. seasonal and inter-annual) ;
- Determine the accuracy of newly developed rainfall estimates for the Regge and Dinkel region;

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 any changes with time(seasons or years)?
- Will the uncertainties in radar based rain estimates be reduced when the *Z-R* relationship is defined based on local gauges?

Study area and data sets

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°08’ - 53°31’N and lat. 6°23’ - 7°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 °C, -0.3 °C and -0.8 °C, respectively (Encyclopedia of the Nations, 2011).

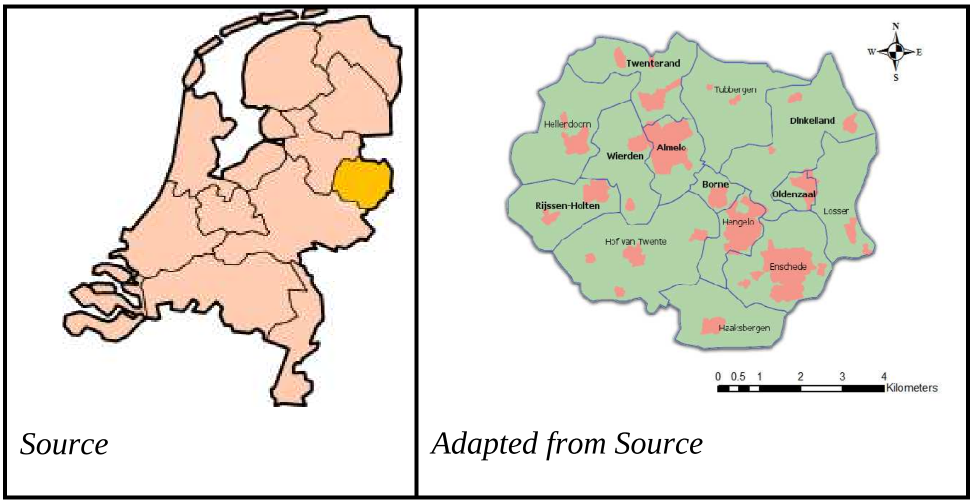


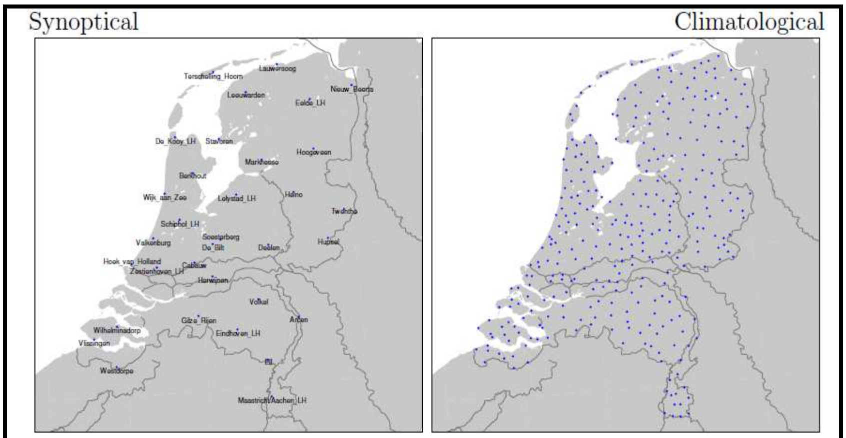
Figure 2: Map of Netherlands (left) showing position of the Twente Area (in orange) and Map of Twente (right)

The average temperature is 2 °C in January and 19 °C with annual average of about 10 °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).
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).

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

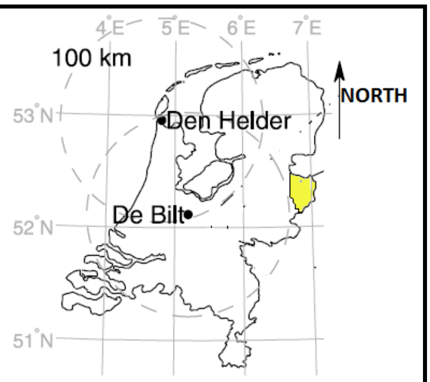
In case of rain events the stations record rainfall amounts with a resolution of 10 minutes (Leijnse, et al., 2007). They use the position of the floater in the cylinder to determine amount of rainfall (Holleman, 2006). Rain gauge data has been obtained from the Water Board from the 18 gauges. These 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[1].

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 13 sites 9 of which are indicated on Table 1 below. 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.

Weather 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],

$$Z = aR^b \qquad (1)$$

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). These were adopted from the Marshall and Palmer *Z-R* relationship (1948). 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 (position shown in yellow in Figure 5) 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.

Pre-processing

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 averaged using a kernel of 3 by 3 pixels centred at the location of each gauge. This section was done using IDL programming in order to speed up the process.

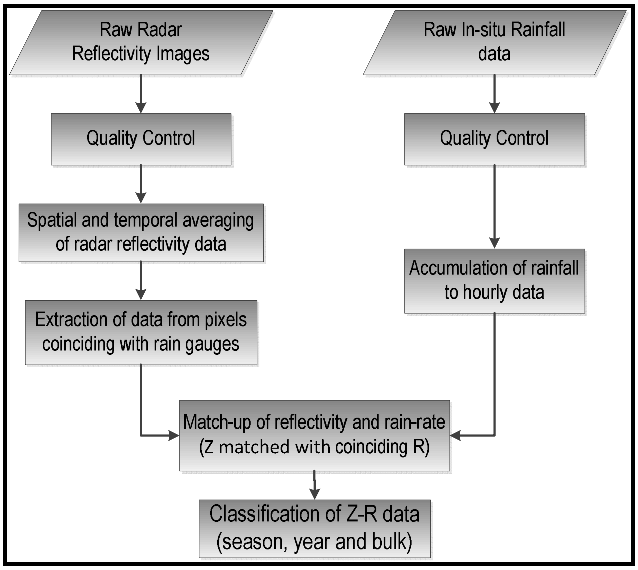


Figure 6: The summary of steps followed during pre-processing

Gauge data pre-processing

Rain gauge data were obtained from the Water Board Regge and Dinkel at 20 minutes resolution for 13 sites. The sites had different data lengths and for this reason this study used data from only 9 sites with periods of lengths shown in Table 1. 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 this study. The data were then computed from 20 minute intervals to a time step of one hour for each location.

The match up of reflectivity and rain rate data

The radar data were obtained using a kernel of 3 by 3 pixels centred above each gauge. 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. Data for Wierdenseveld, Almelo and Losser were used for validation while for the rest of the sites were used for calibration. The *Z-R* data were then organized into 3 classes upon which the *Z-R* relationships were to be established. These classes were the time independent (termed 'bulk' in this study), the seasonal and the 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.

Calibration of the z-r relationship

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 were developed for this district using the rain gauge and reflectivity matchups obtained following the procedure in Figure 7. 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 Water Board. 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).

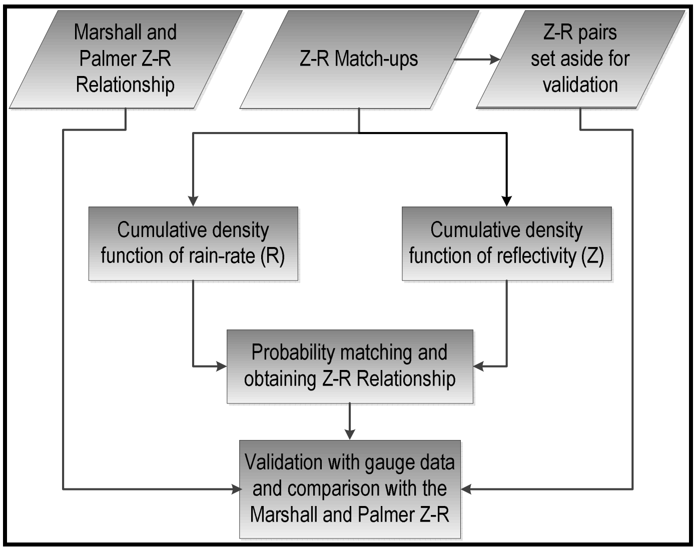


Figure 7: Determination and validation of the *Z-R* relationship

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 a kernel of 3 by 3 pixels and temporally over hourly intervals (Alfieri, *et al.*, 2010;

Fabry *et al.*, 1994; Mapiam, 2008). Calibration is done using window probability matching method also to avoid collocation-related uncertainties (Rosenfeld, *et al.*, 1994).

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

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 1). Huge 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 although in this study the values obtained did not reach that high.

Table 1: Coefficients for Z-R relationships ($Z=aR^b$)obtained

Calibration type	Coefficient *a*	Coefficient *b*
Bulk (general: using all data)	89.1	1.39
Summer	87.6	1.33
Autumn	103.2	1.69
Winter	77.2	1.24
Spring	82.0	1.59
2006	114.5	1.32
2007	70.8	1.55
2008	78.1	1.78
2009	84.1	1.50
2010	95.6	1.13

The *Z-R* relationships were not the same for different years. As an example for 2006 a *Z-R* relationship of $Z=114.4R^{1.32}$ was obtained while it was $Z=70.8R^{1.55}$ for 2007. Alfieri, *et al.*, (2010) did a work in which the *Z-R* relationship was continuously adjusted with time implying that they 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.

VALIDATION

Validation for point measurements

In this step collocation was 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 2.

Contrary to the expectation, the proposed *Z-R* relationships were not giving higher accuracy than the Marshall and Palmer ($Z=200R^{1.6}$). 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 mostly giving higher estimates of rain-rate than the Marshall and Palmer. This was because the proposed *Z-R* relationships have mostly low values of coefficients *a* and *b* 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 mismatch between reflectivity and in situ measurements resulted in the high errors.

Table 2: 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 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. The implication of this is that the radar was not detecting rain-rate in the accurate sense and was thus unreliable. In real time sense reflectivity values were not matching with rain-rate while the *Z-R* relationships assume otherwise.

RESULT AND DISCUSSION

RECOMMENDATIONS

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

- 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. Installation of weather radar/s within or close to the Regge and Dinkel district could be necessary since the available radars are located away from the area.

- 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.
- KNMI should calibrate the radar for other regions of the Netherlands which are within the plausible range of the radar to improve rainfall estimates of the radars.

CONCLUSION

The Marshall and Palmer *Z-R* relationship is currently used by KNMI over the entire Netherlands and for all rainfall types. The relationships between radar reflectivity and rain-rate (*Z-R* relationships) were adjusted to the climatology of the Regge and Dinkel district using reflectivity data from KNMI and rainfall data from the Water Board Regge and Dinkel. However, the Z-R relationships obtained after calibration did not improve the accuracy of radar estimates of rainfall and this was attributed to range degradation as the study area is located in the far eastern parts of the Netherlands and more than 100km from the location of the radar (see Figure 5; position of study area marked by yellow colour). The study recommended use of weather radar whose range adequately covers the area without compromising quality of rainfall estimates.

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