Improving Weather Radar Estimates of Rainfall Using a High Density Rain Gauge Network

Report to the
Water Research Commission

by

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Executive Summary

Background

South Africa has a rich history in weather radars, the first weather radar was installed during the early 1970s by the Council for Scientific and Industrial Research (CSIR). Currently the South African Weather Service (SAWS) operates four old C-band, two mobile X-band and ten S-band radars. The two mobile X-band and ten S-band radars manufactured by Gematronics (now Selex ES) represent the best available technology. Currently the two mobile and the Bethlehem radar have dual-polarization capabilities, however, the nine other S-bands are upgradable at a reasonable cost. Even though the four C-band radars are more than three decades, they have been modified to use a custom-built receiver and this together with the open source Titan software has kept them operational. If well calibrated, the data from these old radars are still useful. This infrastructure provides potential for rainfall estimation, severe storm detection, water management and aviation to name a few.

The current national radar network is plagued by technical problems. A drastic shift towards commercial operation enforced by legislation and dwindling funding has severely limited capacity and resources dedicated to the national weather radar network. This is reminiscent of the shift to market orientated research made by the CSIR in the late 80s.

Rationale

This document describes Project K5/2062 funded by the Water Research Commission. Exciting opportunities arise from the new state of the art weather radar network implemented by the SAWS. The S-band dual-polarized Doppler radar installed near Bethlehem is capable of advanced rainfall estimation as well as precipitation phase identification (differentiation between drizzle, rain, hail, graupel or snow) and severe weather detection. However, the potential of weather radars in South Africa can only be utilized if the appropriate infrastructure and scientific resources are in place.

This project was conceived with the aim to re-establish a high density rain gauge network in order to improve radar rainfall estimates. The Liebenbergsvlei catchment in the Free State was home to a similar network between 1993 and 2001. The loss of skilled engineers, technicians and scientists from SAWS during the last decade has limited the national capacity for scientific research. Having ground-based and remote sensing infrastructure accessible by students and researchers provides a unique opportunity for hands-on training. The data captured by the project can also be used by local and international scientists across a range of disciplines.

Objectives and Aims

Overall, this project aims to develop infrastructure and build capacity to improve rainfall estimation from multiple platforms that is accessible by the scientific community. More specifically, the aims are:

1. To establish a high-density rain gauge network;

2. To establish supporting infrastructure that would provide research data for the scientific community;
3. To advance remote sensing estimates of rainfall in South Africa;
4. To build capacity in rainfall estimation from multiple platforms.

Methodology

The Mooi River catchment was chosen for the high density rain gauge network. The catchment is situated on the Highveld of South Africa between 25° and 26°S latitude and 25° and 27°E longitude and forms part of the Primary Vaal river basin. The catchment covers an area of 3294 km^2 and stretches from 16 km north of Potchefstroom to Derby in the north and the Witwatersrand in the east. The climate of the catchment is moderate with predominately summer rainfall. Rainfall over the catchment is highly variable during large convective storms in the summer months which from occasionally cause severe hail and flash flooding, resulting in millions of rand's worth of damage. The catchment provides a good study area due to its large number of land uses, such as agriculture, urban use, mining as well as low-income settlements. Data from the network can therefore be used for in a number of different disciplines.

The catchment was divided into a 15 km grid. Suitable sites were selected and fifteen automatic rain gauges installed. A custom built, low power logger was designed and deployed for data acquisition. Three test sites were setup in November 2013 and the rest of the network from February 2014 onwards.

Additional infrastructure was deployed as part of this project, this included a Parsivel optical disdrometer and a refurbished WSR-74C C-band weather radar. The radar was installed on a game farm about 10 km north east of Potchefstroom, North-West.

Results and Discussion

Aim 1: Establishing a high-density rain gauge network

A total of three RM Young model 52203 rain gauges and fifteen Hydrological Services PTY LTD model TB3 tipping bucket rain gauges were installed in the catchment. The TB3 gauges are significantly more expensive, it is however the standard model used at all the SAWS automatic weather stations. The final set of data was quality controlled and resampled to a regular 1-minute data set of rain rates between 6 November 2014 and 23 June 2015,

Aim 2: Supporting infrastructure to study rainfall

An OTT Parsivel disdrometer was deployed in the catchment. It is an optical rain gauge that uses cutting edge laser technology to measure rainfall. A laser beam is used to measure the velocity and diameter of the particle moving through the beam, the loss in voltage is measured and converted into aspects of rainfall such as intensities and amount. The Parsivel disdrometer has a sampling area of about 54 cm^2 and measures particle sizes which can reach up to 25 mm and velocities between 0.2 and 20 $m.s^{-1}$. The particles are then categorised into 1024 classes of size and velocity and is displayed on a 32x32 matrix. This instrument is useful for radar calibration purposes as it can help us determine the necessary Z-R relationship needed for calibrating the weather radar network.

In addition, an old WSR-74C radar was acquired from Texas, USA. A radar site was chosen with an optimal coverage area, this was located about 10 km north east of Potchefstroom on the Lekwena game lodge, also the radar's namesake. The transmitter was re-engineered to use a modern, off-the shelf digital transmitter solution produced by Pulse Systems Inc.

Aim 3: Advancing remote sensing estimates of rainfall in South Africa

Radar estimates of rainfall over South Africa is well described in literature. Dual-polarized radars are capable of accurate rainfall estimates as well as hydrometeor classification. It is further possible to detect and remove unwanted noise from the reflectively fields. Although there are three dual-polarized radars in South Africa, none of the data was available for this project. It is clear that keeping the current infrastructure in a calibrated, working order is crucial

Currently, SAWS uses the Marshall-Palmer Z-R relationship to convert reflectivities to rainfall. With only radar reflectivities and Doppler velocities available, the options for advance rainfall retrievals are limited, an improvement to the current approach is to use a customized Z-R obtained by using a Parsivel disdrometer. For convective events, the coefficients were $Z = 186r^{1.5}$ and for stratiform events $Z = 241r^{1.5}$. A new algorithm in Titan can be used to stratify storms into their convective and stratiform components.

Aim 4: Building capacity in rainfall estimation

Three MSc, one MIng and five BSc Hons students were trained as part of the project. Students got the opportunity to be part of the installation, calibration and maintenance of tipping bucket rain gauges, an optical disdrometer and a weather radar. All of the students are expected to finish their degrees at the end of 2015.

A workshop was held in collaboration with a leading international expert on weather radar in 2012 and an open invitation was sent to the research community. Three members of SAWS attended this workshop. The project team further collaborated with SAWS to deliver three '*Introduction to Weather Radar*' workshops between 2013 and 2014. Three SAWS technicians were invited to be part of the installation and re-engineering of the Lekwena radar.

Links with the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. USA were further strengthened as part of the project. NCAR is the custodian of the Titan radar software. This currently forms the backbone of the national radar network. Two of the NCAR scientists were appointed as extra-ordinary associates of the North-West University (NWU). A memorandum of understanding (MOU) regarding collaboration and sharing of intellectual property on weather radar is currently being written.

CONCLUSIONS

Weather radar is an unparalleled tool to study and quantify storms and precipitation. South Africa is equipped with state of the art infrastructure, however, capacity and resources are lacking. An effort is underway to establish a centre of excellence in observing precipitation. The high density rain gauge network, the optical disdrometer and the Lekwena radar forms the backbone of these activities. The infrastructure provides access and data to the South African scientific community. A data set from a high density rain gauge network has been gathered for the 2014-2015 season.

The life of old Enterprise radars can be extended by re-engineering obsolete components. The transmitter of the Lekwena radar was successfully replaced using the off-the-shelf solution produced by Pulse Systems Inc. A custom-designed low power logger was developed for rainfall estimation, these loggers can also accommodate soil moisture and analog measurements.

RECOMMENDATIONS FOR FUTURE RESEARCH

Capacity building in weather radar remains a major concern. Workshops, training sessions, and access to operational radars need to be prioritized. Access to data for research purposes is restricted. The pressures of limited resources and a commercial environment put science on a low priority. The infrastructure developed as part of this project provides research grade data to the scientific community. It is our hope to continue building this as a national resource.

The rain gauge network is currently not automated. Low power modems need to be developed to transmit data to a central server. These resources need still have to be put in place.

The current network density of the rain gauges can still be improved. The spatial variability cannot be sampled at spatial scales less than 20 km and temporal scales less than 12 hours. Increasing the density will make it possible to study additional research problems.

A modern radar receiver will make it possible to extend the life of approximately eight old weather radars in South Africa. The technology for this upgrade has been identified. The Lekwena radar can be used as a test bed for new improvements.

Acknowledgements

This project was funded by the Water Research Commission.

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The Reference Group for the project was:

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Mr Pieter Visser	Aon-Benfield
Prof. Francois Engelbrecht	Council Scientific and Industrial Research
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Dr Scott Sinclair	University of KwaZulu-Natal
Mr Eugene Poolman	South African Weather Service
Mr Johan Malherbe	Agricultural Research Council

The following MSc students have incorporated the project activities in their thesis (name, year completing their degree):

Jaun van Loggerenberg	2015
Reinhardt Hauptfleisch	2015
Ryno Du Preez	2015
Michael Benjamin	2015

The following Honours students have incorporated the project activities in their research projects:

Keorapetse Moeketsi	2016
Nisa Ayob	2015
Karabo Molapo	2015
Thalita Botha	2014
Henno Havenga	2014

The North-West University provided funding from their Research Infrastructure Fund as well as from the Unit for Environmental Sciences and Management, through its director Professor Nico Smit, to install and upgrade the NWU Lekwena radar.

ALS group provides the site for the Lekwena radar at no cost to the NWU.

Funding was obtained from the National Research Foundation 2014 equipment related travel and training grant to visit institutes and companies in the United States of America to build capacity around weather radar at the North-West University.

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Abbreviations

AWS	Automated Weather Station
CSIR	Council for Scientific and Industrial Research
DARAM	Daily Mapping over South-Africa
DWA	Department of Water Affairs
ESD	Electronic Systems Development
NCAR	National Center for Atmospheric Research
NPRP	National Precipitation Research Program
NWU	North-West University
SAAF	South-African Air Force
SAWS	South-African Weather Service
SIMAR	Spatial Interpolation and Mapping of Rainfall
VIPOS	Vaal Dam Integrated Precipitation Observing System
WRC	Water Research Commission

1. Introduction

The management of water resources is a growing issue globally. The consumption of freshwater has tripled worldwide over the past few decades and it is continuing to increase. It was estimated that nearly a billion Africans will be living in water stressed countries by the year 2025. This is an issue of global concern and thus an integrated water management approach is needed to insure future water resource sustainability (Terblanche et al., 2001a).

South Africa is a semi-arid country where more than half of the country receives less than 500 mm per year on average. The large inter-annual variations of rainfall caused by South Africa's location between the sub-tropics and mid-latitudes characterize the challenges facing water resource management in South Africa. A large percentage of rainfall in South Africa is produced by convective storms which can potentially cause severe flash flooding, hail and other storm-related damages. These types of storms produce rainfall fields with high spatial and temporal variability, making it very important to monitor and measure rainfall (Shippey et al., 2004). Rainfall measurements over large areas is required as input data for a whole range of applications which range from real time warning systems in hydrology and meteorology to complex models for investigating the aftermath of critical events. Applications such as these all require precise and representative estimates of rainfall.

Weather radar is one of the most advanced tools available for rainfall studies. The new South African radar network represents the latest, most up-to-date technology. This puts South Africa in the leading sector of international radar rainfall studies. The introduction of dual-polarized technology has not only improved rainfall estimations but also identification of various processes within clouds, for example rainstorm phase analysis (differentiation between drizzle, rain, hail, graupel or snow) is now also possible. The new radars also have Doppler capabilities, which provide information of the movement within storm cells. The validation of such powerful radar technology using rain gauge networks will add immensely to scientific findings both locally and internationally.

1.1. Background

Twelve new Doppler radars are installed around the country. These include ten S-band radars, nine of which are horizontally polarized and one is dual polarized, and two mobile dual polarized X-band radars that is to be placed at OR Tambo International Airport and Cape Town International Airport.

The major advantages of installing this new network are the Doppler capabilities of the new radars as well as the dual polarization capabilities of the Bethlehem radar and the mobile systems. With dual polarized radars, electromagnetic waves are polarized in both the vertical and horizontal planes. Dual polarized radars have a wide range of capabilities, which include: distinguishing between meteorological and non-meteorological targets; improvements in data quality compared to regular Doppler radar; improvements in rainfall measurement accuracy when compared to standard Z-R (Reflectivity-Rain rate) methods; and the provision of a platform for the classification of different hydrometeors (Bringi and Chandrasekar, 2005; Rinehart, 2004).

Information on the size, type and shape of a cloud can be determined with a dual polarized radar by comparing the reflected horizontal and vertical signal returns, their ratios and the correlation between them. These ratios and correlations are referred to as polarimetric variables and have been utilised in various rainfall estimation projects around the world (Liu et al., 2000; Straka et al., 2000; Zrnic et al., 2001; Gorgucci et al., 2006; Teschl et al., 2008; Paulitsch and Teschl, 2008; Paulitsch et al., 2009). Such studies have yet to be investigated for South African. If estimation algorithms using such variables prove advantageous over the existing Z measurement estimations, this will provide the South African Weather Service (SAWS) with enhanced real time rainfall estimations, providing better forecasts and in turn, creating improved warning systems. Such a study will also be part of the motivation to upgrade the other nine Doppler radar systems to include dual polarized measurements.

Traditionally, rain gauges have been an important rainfall measurement tool, however, they no longer meeting modern monitoring and information system requirements. With technological advances, radar and satellite measurements have emerged. These new technologies do, however, require validation with measurements on the ground. Rain gauge networks in South Africa and around the world are deficient, especially if area's rainfall is to be determined and validated. Despite these limitations, rain gauge networks remain the most trusted point measurements of rainfall to date and is widely used as a validation tool for radar and satellite rainfall measurement adjustments (Kroese et al., 2006). Rain gauge measurements also provide an important climatological link with historic data sets.

In 1993, a network of rain gauges was established in the Liebenbergsvlei catchment area near Bethlehem, Free State to provide validation and verification of the National Precipitation Re- Search Program (NPRP) (Mather et al., 1996, 1997b). The data from the rain gauge network was not only utilised in the NPRP for rainfall enhancement projects, but also become a valuable verification tool for radar rainfall studies. These studies enabled possible solutions to agricultural and climatological issues in the region (Kroese, 2004). Together with the MRL5 radar near Bethlehem, the rain gauge network proved highly useful for the Department of Water Affairs and Forestry during the 1996 floods of the Vaal catchment. During these floods the comparison of the radar- rainfall measurements to the 45 gauges in the Liebenbergsvlei catchment came to within 3% of each other (Mather et al., 1997a). During the 1995/1996 season, Mittermaier and Terblanche (2000) developed a new algorithm to integrate radar rainfall estimates and rain gauge data from the Liebenbergsvlei catchment. This was found to improve the spatial rainfall estimates. The study was representative of ideal conditions, so it was noted that future studies required radar-rainfall fields with low data density on a daily basis.

Data from the Liebenbergsvlei network also played an important role in the Vaal Dam Integrated Precipitation Observing System (VIPOS) project. During the 1998/1999 and 1999/2000 seasons various studies were performed to validate and improve radar calibrations, assess rainfall estimation procedures and to identify potential problem areas.

VIPOS clearly showed that radar estimated rainfall fields can be improved by utilising rain gauge adjustments. VIPOS lead to the development and testing of the first integrated radar and rain gauge information system for South Africa. The system used the wetted area ratio to determine the extent to which radar fields should be adjusted according to rain gauge measurements (Terblanche et al., 2001b).

From the VIPOS project, concern regarding the accessibility, reliability and coverage of the rain gauge network was raised. Improvements to the existing rain gauge network infrastructure to include a real time data base was stressed, provided that this did not compromise on data quality (Terblanche et al., 2001a). In 2001, the Spatial Interpolation and Mapping of Rainfall (SIMAR) project was initiated which aimed to provide a daily precipitation estimate for South Africa, it was a first time approach at integrating radar, rain gauge and satellite data into a consolidated rainfall map. Since 2003, the product has become operational and daily integrated rainfall maps can be accessed from the SAWS website. During SIMAR, the rain gauge networks in both the Liebenbergsvlei and Durban areas played an important role in radar analysis. This included the elimination of ground clutter as well as validating the radar-rainfall estimations on the ground (Kroese, 2004). Most recently, the Daily Mapping over South Africa (DARAM) project was initiated to improve upon the real-time precipitation measuring infrastructure for hydrological and flood warning applications as well as establishing a real-time precipitation database. With the introduction of DARAM, daily rain gauge measurements were required, hence the manual rain gauges that were initially installed, would no longer be sufficient. Upgrading to electronic real- time gauges was essential (Kroese et al., 2006).

After some years, due to financial and technical constraints, it was agreed that the Liebenbergsvlei network of rain gauges were not functioning on a sustainable basis. To overcome this, in 2003 the 45 existing manual rain gauges were replaced with 20 automated tipping bucket rain gauges equipped with real-time cell phone communication technology. The only problem with these new rain gauges was the replacement of the batteries every 3 to 4 months which contributed to high operational costs. The solution to this was the installation of a solar panel at each site to recharge the batteries, which did not only aid in extending their lifetime, but also their time in operational use (Kroese, 2004). Although this new rain gauge network is a major technological improvement on the original net- work, there are not enough sites to be spatially representative of the area. As a result, the rain gauge network has slowly disintegrated over the last few years and is currently not utilised to its full potential, as it was in the past. The current commercial focus of SAWS further hampers access to data, not only from gauges in the Liebenbergsvlei catchment, but also other infrastructure it owns.

The original dataset from the Liebenbergsvlei catchment have been used extensively in research. Applications include improving radar estimates of rainfall (Wesson and Pegram, 2006;Kroese et al., 2006;Deyzel et al., 2004;Pegram and Clothier, 2001;Terblanche et al., 2001a;Mittermaier and Terblanche, 2000), hydrological modelling (Vischel et al., 2008;Clothier and Pegram, 2002; Pegram and Sinclair, 2002; Sinclair, Scott and Pegram, 2004) and application of satellite remote sensing to water resources management

(International Hydrological Programme, 2010;Sinclair and Pegram, 2009; Vischel et al., 2007).

The benefit of an accessible, high density network of rain gauges, combined with radar data can therefore not be underestimated.

A drastic shift towards commercial operation enforced by legislation and dwindling funding has severely limited capacity and resources dedicated to the national meteorological observation network operated by SAWS. Data availability for research is sparse and SAWS provides a second rate service with limited access for non-funded projects. This problem currently plays itself out in many countries and a general downward trend in meteorological infrastructure is typically justified with the advances in remote sensing.

Since the old rain gauge network proved useful in the calibration of old radar data, a new rain gauge network would be highly beneficial to complement the new, state-of-the-art radar network. Therefore, the reestablishment of a high density catchment rain gauge network is warranted.

1.2. Study objectives

Overall, this project aims to develop infrastructure and build capacity to improve rainfall estimation from multiple platforms that is accessible by the scientific community. More specifically, the aims are:

1. To establish a high-density rain gauge network
2. To establish supporting infrastructure that would provide research data for the scientific community
3. To advance remote sensing estimates of rainfall in South Africa
4. To build capacity in rainfall estimation from multiple platform

2. Data and Methods

2.1. The Mooi river high density rain gauge network

A total of 21 automatic rain gauges was installed in a section of the Mooi river network between 2012 and 2014 (Figure 2.1). This chapter describes the design and methods used in developing this high density rain gauge network.

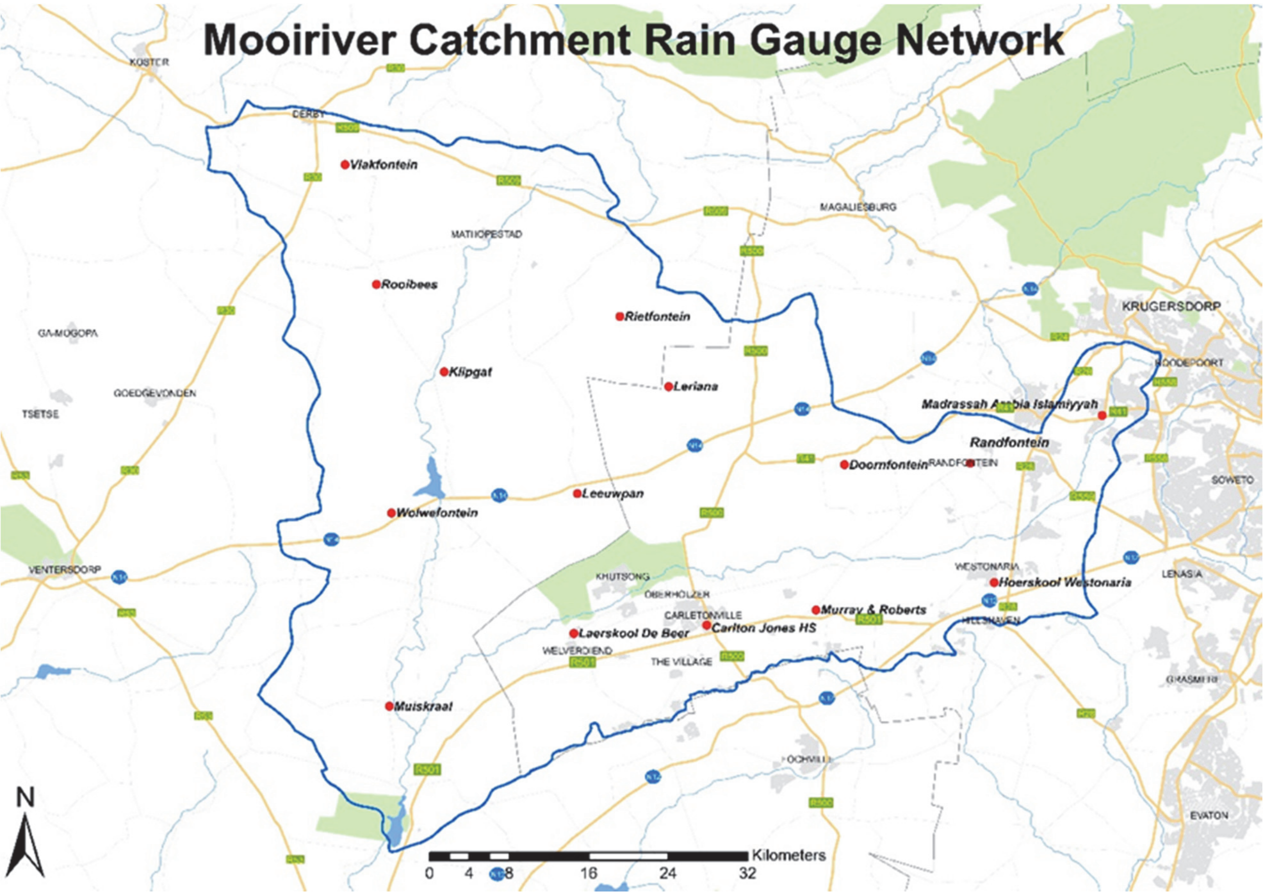


Figure 2.1: The location of the rain gauges installed for this study. The site at the North-West University (NWU) and Lakwena radar is not shown.

2.1.1. The Mooi river network

The area where the rain gauge network is installed is called the Mooi river network (Figure 2.2). It is however not the official name of the catchment as it is in fact a grouping of 4 quaternary catchments of the Mooi river and the Mooi river loop. The Mooi river network is situated on the Highveld of South Africa between 25° and 26°S and 25° and 27°E and forms part of the Primary Vaal river basin. The catchment covers an area of 3294 km^2 and stretches from 16 km north of Potchefstroom to Derby in the north and the Witwatersrand in the east. The climate of the catchment is moderate with predominately summer rainfall occurrence. The rainfall over the catchment is, however, highly variable especially during large convective storms in the summer months which from time to time causes severe hail and flash flooding.

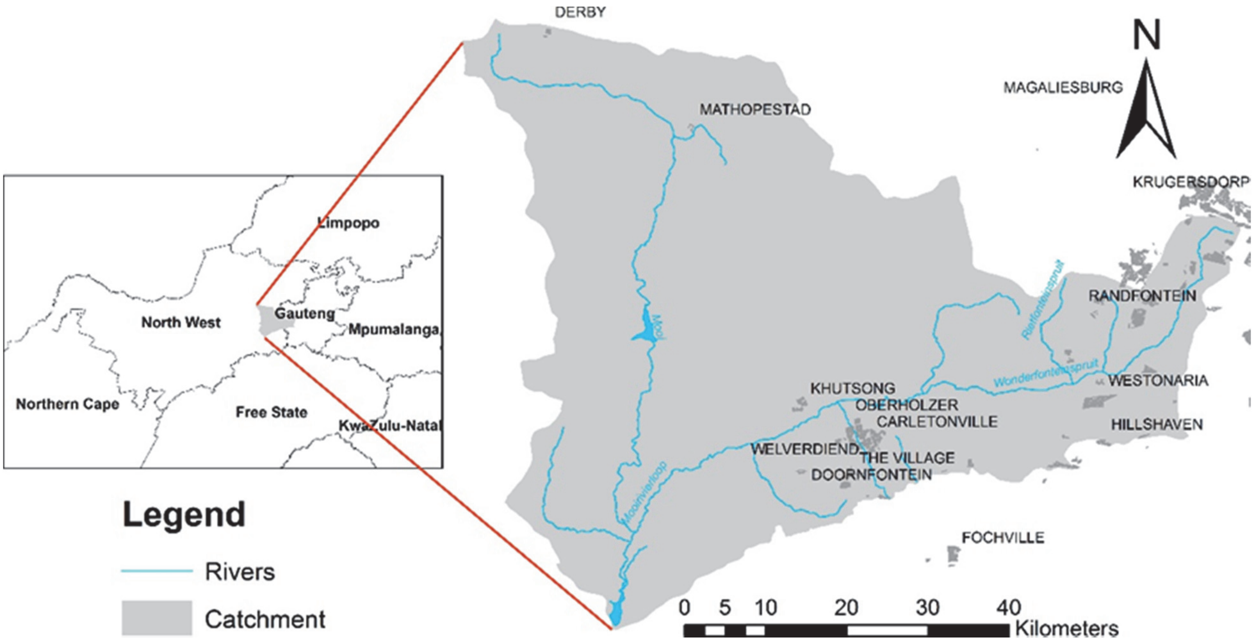


Figure 2.2: The geographic location of the Mooi river network as defined for this study.

2.1.2. Topography of the Mooi river network

The catchment sits at an average elevation of about 1500 m above sea level. Parts with the highest gradient are found in the eastern parts where the catchment meets the escarpment of the Wit Waters Rand (Figure 2.3). The eastern parts of the catchment are the most populated parts of the catchment and it is also in these parts where flash flooding occurs the most as a result of the steep topographical gradient.

2.1.3. Landuse in the Mooi river network

The main economic activities in the Mooi river network is agriculture and gold mining. Knowing the climate and rainfall variability of the Mooi river catchment is of great importance to these two industries and therefore it was decided that a rainfall monitoring network in this area will contribute a great deal of information on rainfall for these two industries. All of the rain gauges in the western and northern parts of the catchment are located on commercial farms that practices dryland farming, rainfall is of critical importance to these farmers as their livelihood depends on it (Figure 2.4, 2.5 and 2.6). The other rain gauges in the catchment are all placed in urban areas where flash flooding regularly occurs during large convective storms.

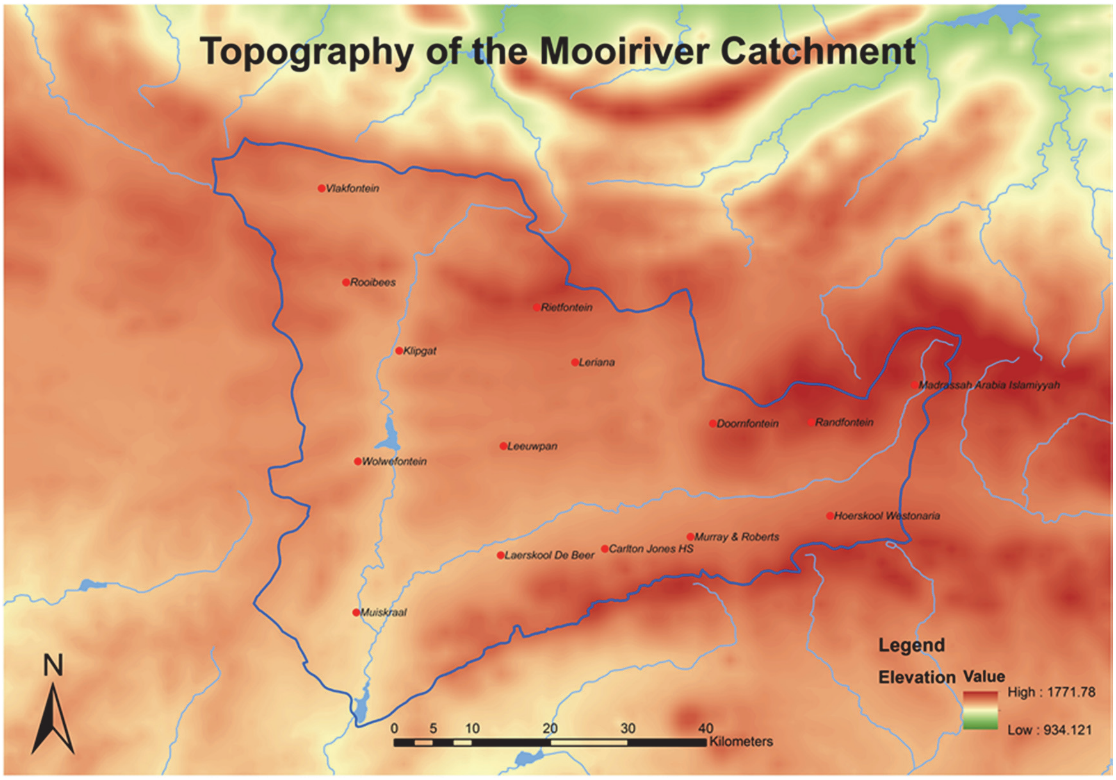


Figure 2.3: The Topography of the Mooi river network. The positions of the newly in- stalled Mooi river network rain gauges (red circles) are shown.

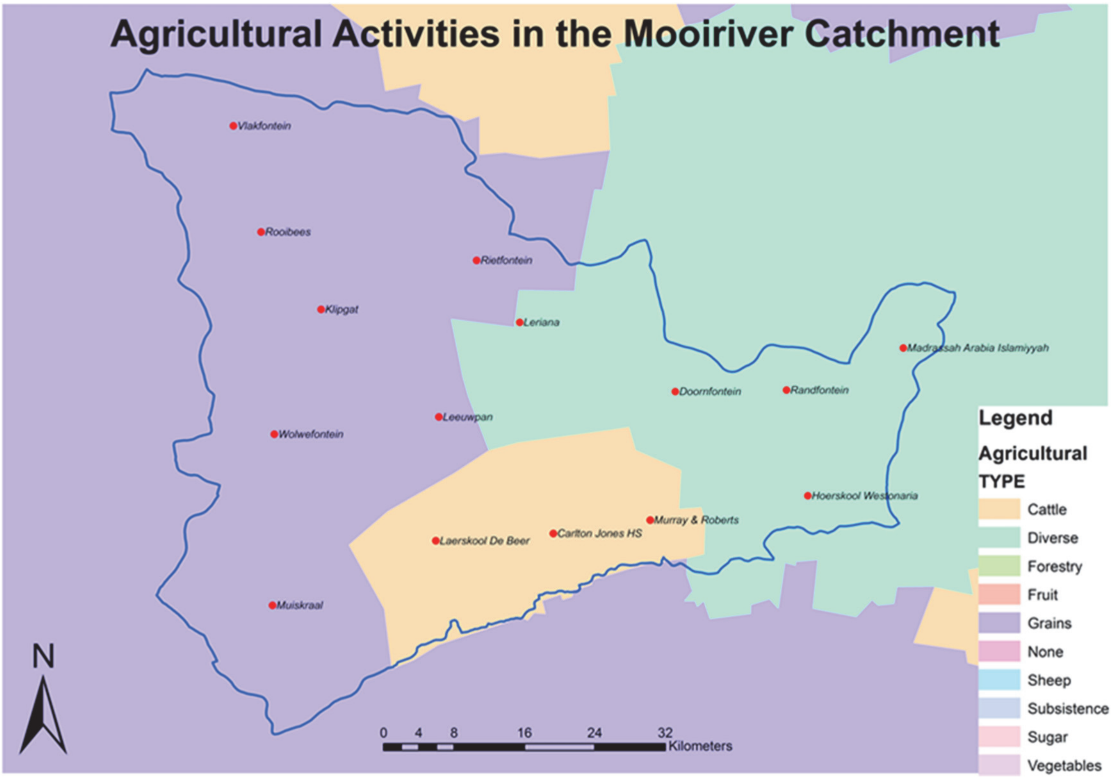


Figure 2.4: Agricultural activities in the Mooi river network. The positions of the newly installed Mooi river network rain gauges (red circles) are shown.

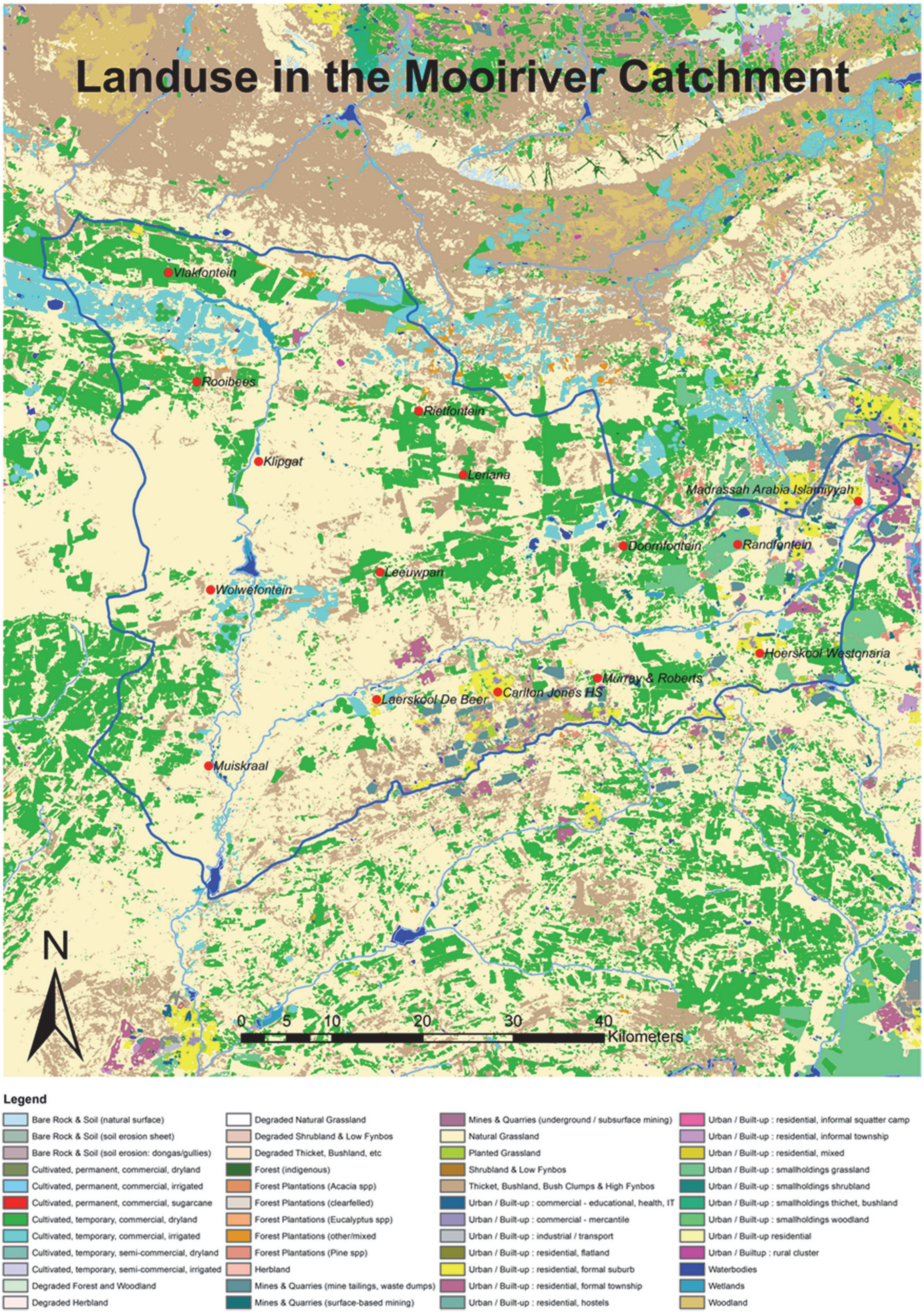


Figure2.5: The land use of the Mooi river network and its surrounding area.

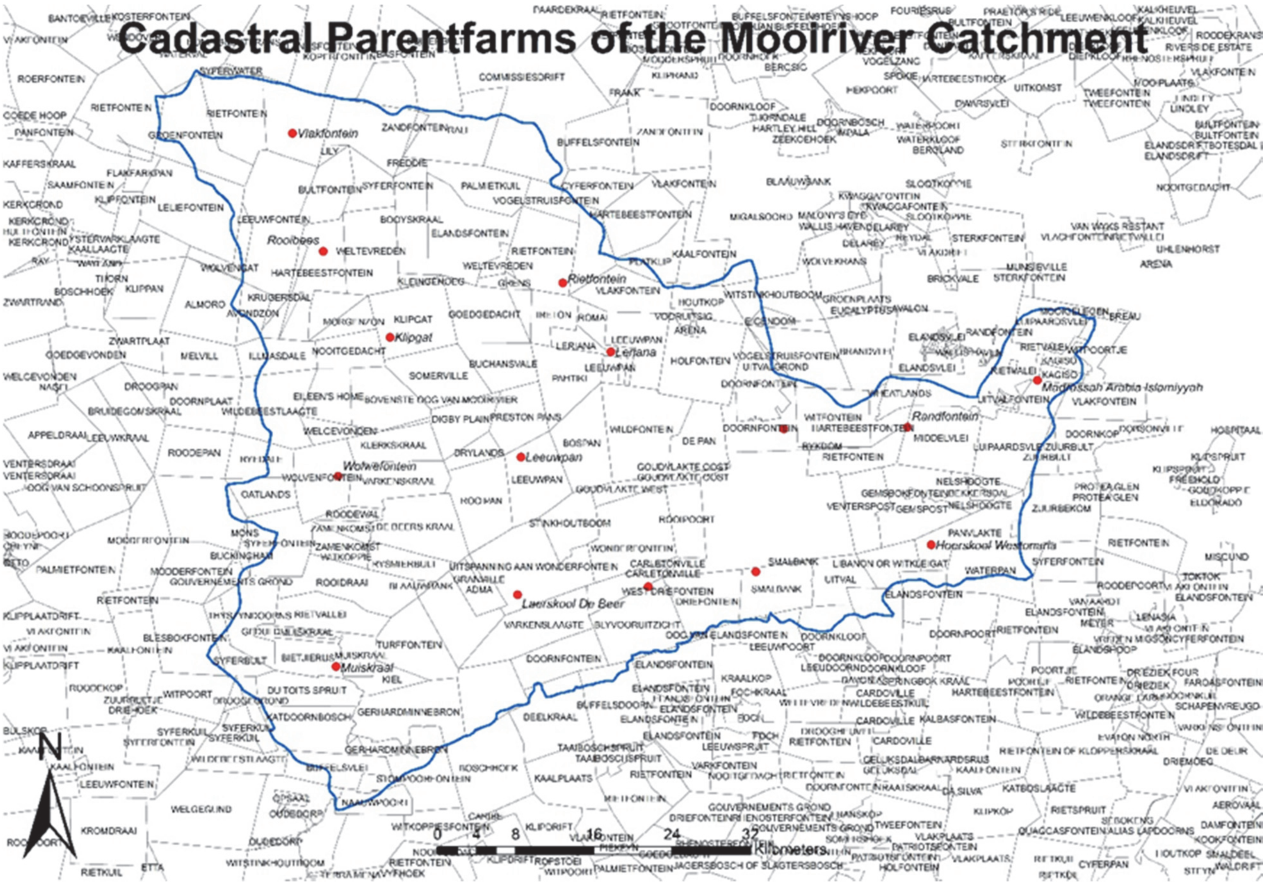


Figure 2.6: Farms in the Mooi river network.

2.1.4. Geology of the Mooi river network

The geology of the Mooi river network (Figure 2.7) consists mainly of carbonate rocks called dolomites. Dolomites are known for forming sinkholes. Carletonville which is located in the southern part of the catchment is notorious for sinkhole formation in its surrounding areas. In 1964 two houses of the town completely disappeared down a massive sinkhole taking a whole family down with it. Sinkholes form when rainfall percolates into the soil and reacts with carbon dioxide to create slightly acidic water that moves into the cracks of the dolomites and slowly dissolves the rock until the cavities that are made in the dolomite collapses on itself and thus forming a sinkhole. Because rainfall plays such a big part in the formation of sinkholes the rain gauge network will also assist us in monitoring the formation of sinkholes by comparing the amount and rate of rainfall over time with the formation of sinkholes. Doing this will help us in identifying the relationship that rainfall has to sinkhole formation in the area in order to ultimately predict the conditions that are prone to sinkhole formation

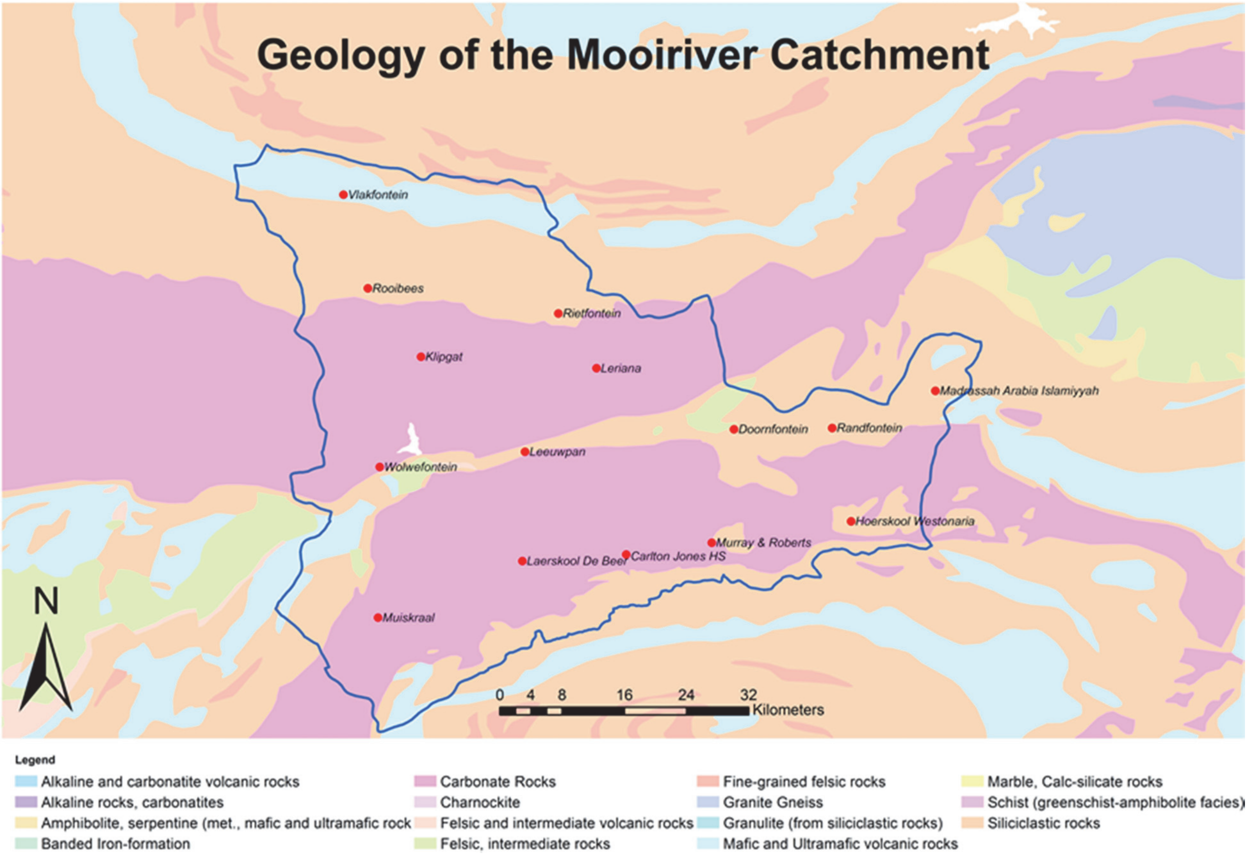


Figure 2.7: Geology of the Mooi river network.

2.1.5. SAWS rain gauges in the Mooi river network

The Mooi river network and its surrounding areas are also home to several South African Weather Service rain gauges (Figure 2.8). Most of these SAWS rain gauges can give historical daily rain rainfall records back to the 1960s. There are also a few of the SAWS rain gauges that are capable of providing 5-minute rainfall records from the late 1990s until present.

The SAWS rainfall monitoring network in the Mooi river network area is a great advantage to the newly installed Mooi river network rain gauge network as the data from the SAWS network which has been up and running for decades can be compared to the data from the new network in order to assess the quality and consistency of data from the two networks.

2.1.6. DWA flow gauges in the Mooi river network

Other valuable research infrastructure that is available in the Mooi river network is the substantial number of DWA flow gauges in the Mooi River and Mooi river loop (Figure 2.9). Data from these flow gauges can give clear picture of the amount of runoff water that accompanies rainfall events. Using both the data from rain gauges and flow gauges in the Mooi river catchment, in depth hydrological and climatological studies can be done of the about the variable and dynamic nature of water in the Mooi river Catchment.

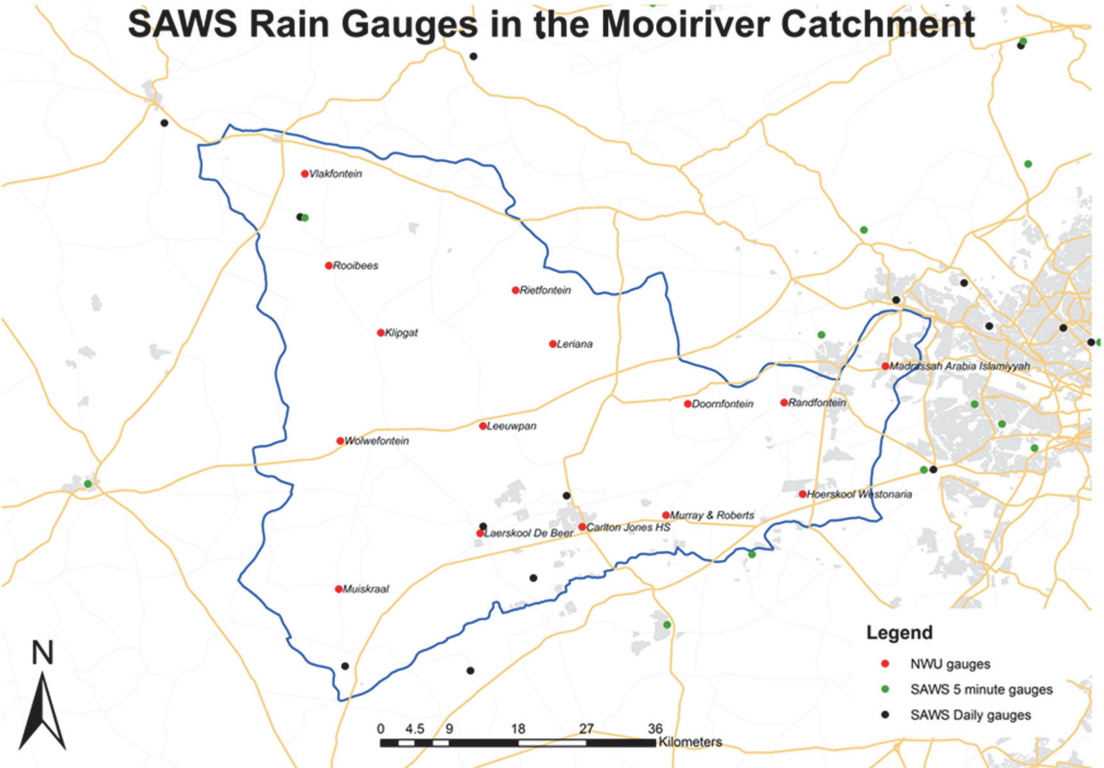


Figure 2.8: SAWS rain gauge infrastructure in the Mooi river network area.

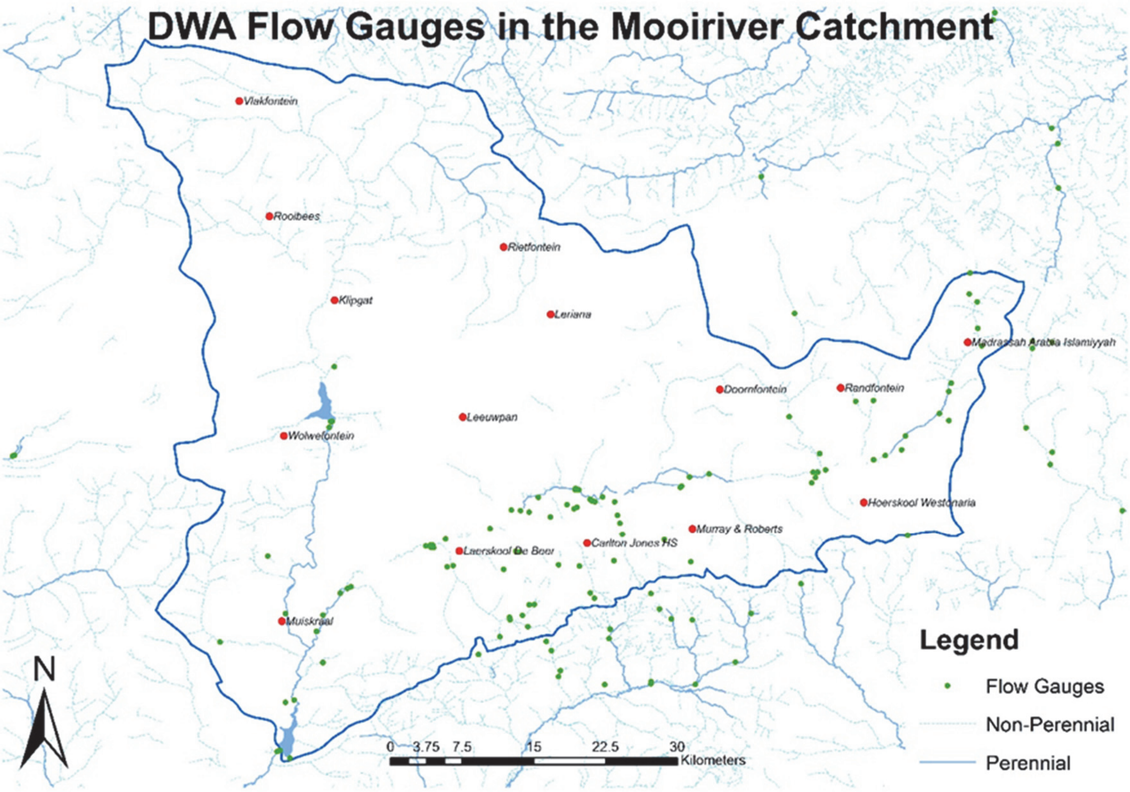


Figure 2.9: DWA flow gauges in the Mooi river network area

2.1.7. Instruments deployed in the Mooi river network

RM Young Model 52203 Tipping Bucket Rain Gauge

For the sub grid scale rain gauge study, three RM Young, model 52203 tipping bucket rain gauges were chosen (Figure 2.10). The three rain gauges were placed between six different maize crops. The purpose of these rain gauges is to measure the rainfall on a small scale at various locations. All three of these rain gauges were are equipped with individual data loggers (Electronic Systems Development logger ELOG 1), that is calibrated to record tips.

The tipping mechanism consists of a top and a bottom part. The top part of the mechanism is held in position by a magnet. When it rains, the water moves from the funnel into the top part of the tipping mechanism. The calibrated amount for this model is 0.1 mm of rain. When the amount of water in the tipping bucket reaches 0.1 mm, the magnet will release the top part and then it tips. This tip is then recorded to the logger. Data is downloaded from the logger every second week.

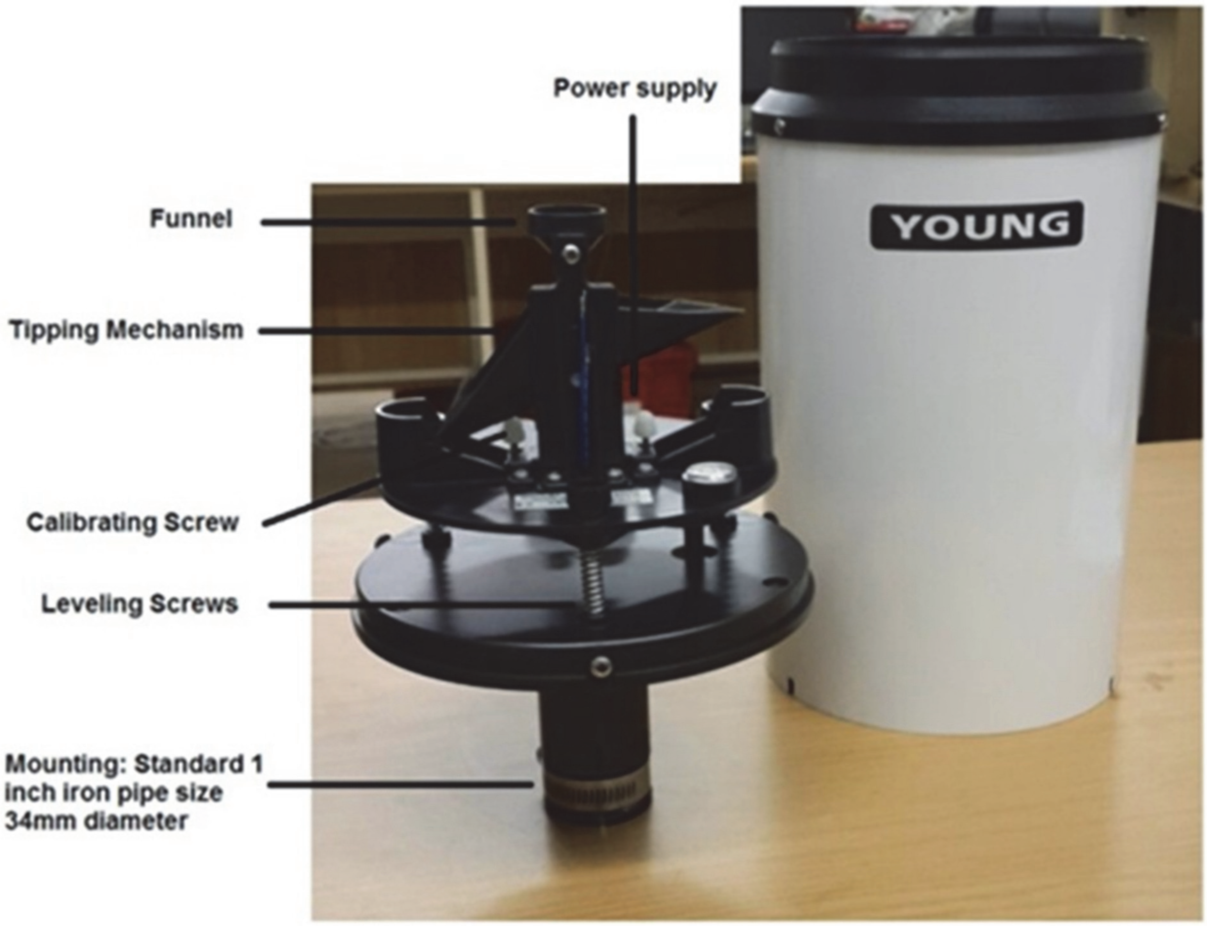


Figure 2.10: The RM Young model 52203 tipping bucket rain gauge

Hydrological services TB3 tipping bucket rain gauges

For the second phase of the Mooi river rain gauge network, fifteen rain gauges were installed. The rain gauges that were chosen for the network are TB3 tipping bucket rain gauges manufactured by Hydrological Services PTY LTD (figure 2.10 and 2.11). The TB3 tipping bucket is also the same type rain gauge used by the SAWS at all of their automated weather stations. These rain gauges are very reliable and recognized worldwide as one of the standard devices for measuring rainfall in remote and unattended locations. TB3 tipping bucket rain gauges are great at giving accurate high resolution data of rainfall in real time. The accuracy of the TB3 rain gauge is not affected by rainfall intensity and it has a long term stable calibration. The measuring system of these rain gauges is based on two tipping buckets on a horizontal pivot (figure 2.12) which tips over once rain of 0.2 mm is collected in one of the two buckets. The gauge has a reed switch output with no correction for faulty tips. The TB3 proves to be a rugged, reliable gauge. It has protection against bugs and only slightly underestimates high rain rate events in access of 500 $mm.h^{-1}$. The stated maximum rain rate is 700 $mm.h^{-1}$. The manufacturer states an accuracy of ±2% for rain rates between 25 and 500 $mm.h^{-1}$. Comparisons with other gauges have been favorable

Another feature of this rain gauge is the integrated syphon mechanism (Figure 2.12), which ensures that measurements are taken with a high level of accuracy across a broad range of rainfall intensities. The syphon acts as a flow control at the exit of the funnel to reduce rain rate errors common to tipping bucket gauges. The syphon lets the water drain out of the funnel at a constant rainfall rate to the buckets of the rain gauge. This sets the momentum transferred to the buckets which would otherwise change as the rainfall rate changes (Devine and Mekis, 2008).

Other features of interest on the TB 3 rain gauge is the various filters and screens fitted to keep debris and insects out of the essential parts of the rain gauge. This prevents stoppages and jamming of parts such as the pivot of the rain gauge (Figure 2.11 and 2.12).

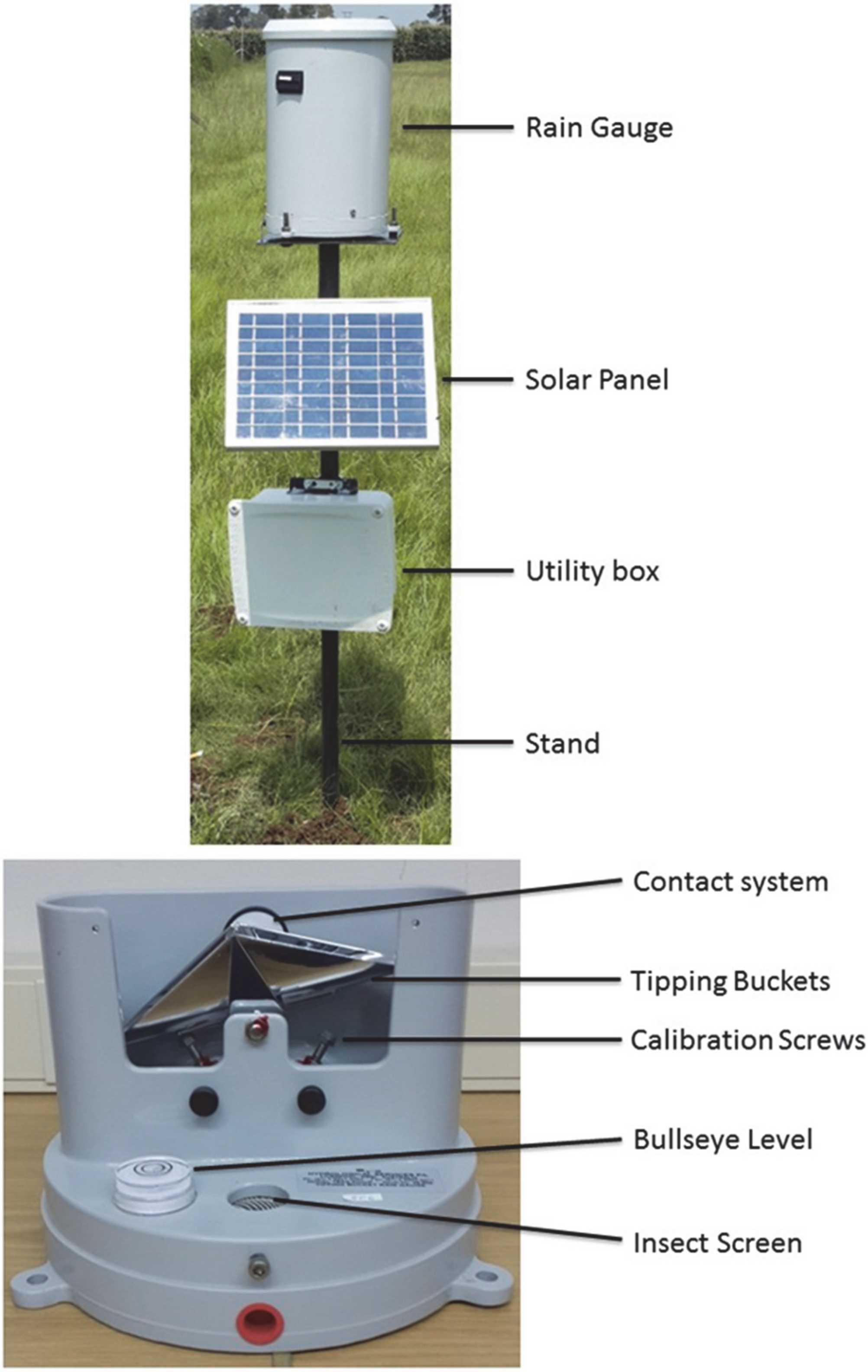


Figure 2.11: The TB3 tipping bucket rain gauge. The top picture shows an installed rain gauge. The bottom one shows the TB3 without its enclosure.

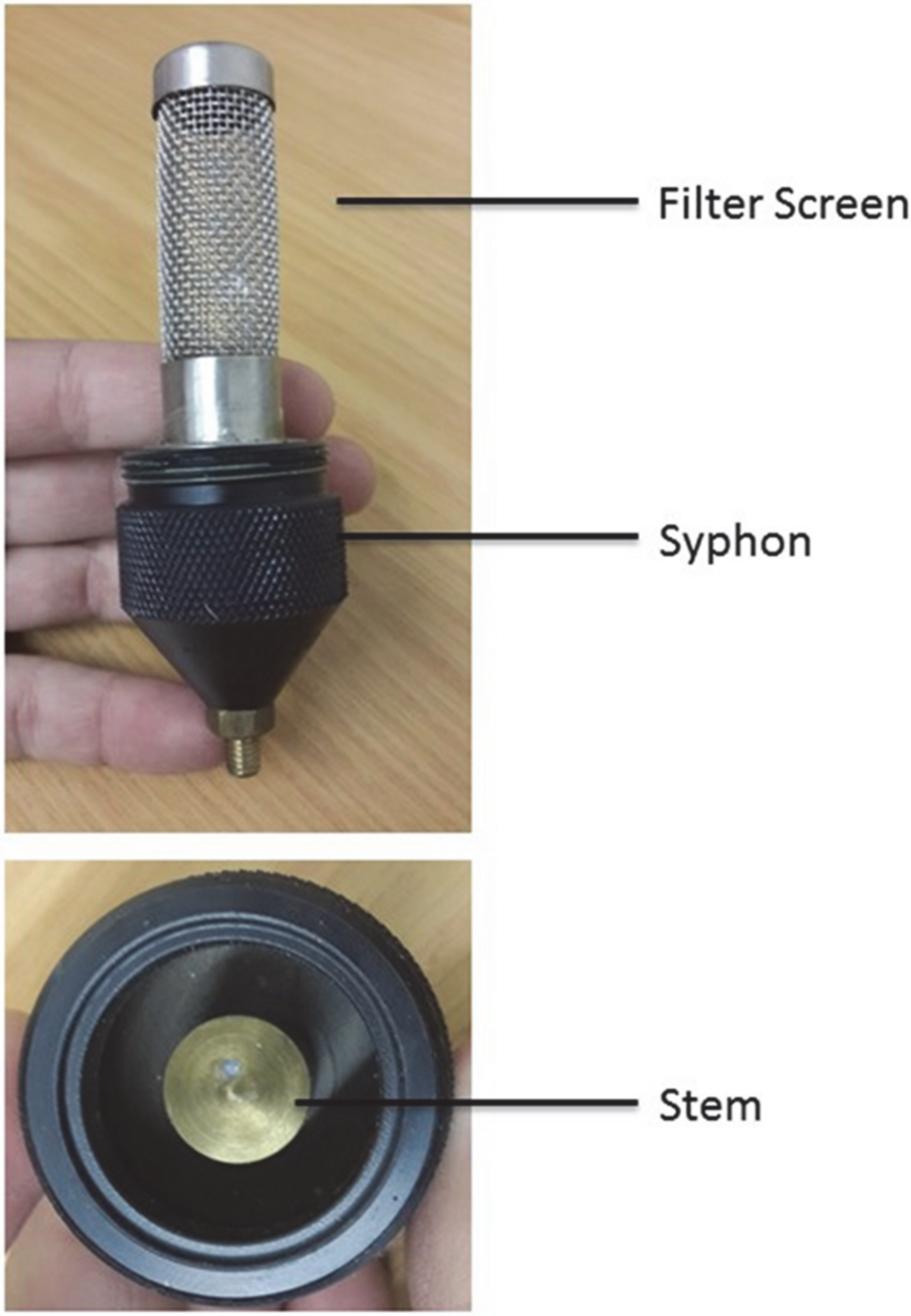


Figure 2.12: The TB3 syphon mechanism.

2.1.8. Maintaining the Mooi river network

A rain gauge that is left unmaintained will quickly lose the degree of reliability and data quality required its by users. Because of this each rain gauge in the network is visited once a month during the rainfall season and in the dry season the rain gauges are visited once every 2 months. During each visit the catch and syphon of the rain gauge is cleaned of insects or debris present. An in situ calibration test of each rain gauge is done in order to check if the rain gauges are still properly calibrated. Furthermore, the data logger is also calibrated and updated, as time-drifting of the logger programming can become an issue when high resolution real-time data is required of rainfall.

2.1.9. Calibrating the tipping bucket rain gauges

A model 52260 Young calibration kit was acquired to check the functioning of the tipping bucket gauges (Figure 2.13). Each gauge was calibrated before deployment and is check in the field during every maintenance visit. The rain gauge calibrator enabled us to test the calibration of the rain gauges under various flow rates (50, 75, 100 mm/hour) in order to simulate different rainfall rates. According to the calibration chart of the TB 3 rain gauge, 500 ml of water should under calibrated circumstance result in 79.99 tips of the buckets in the rain gauge.

Figure 2.13: The tipping bucket calibration kit

2.1.10. Electronic data loggers

The logger is an extremely important part of the rain gauge infrastructure. A reliable, low-power logger can decrease the service interval and improve data retention. For this reason, the data logger we chose is an ELOG1 logger manufactured by Electronic Systems Development (Figure 2.14).

The data logger has 4 gigabyte of storage space which gives it a capacity of recording 6.5 million tips corresponding to 130,5882 mm of rainfall, this is enough storage space to record rainfall data non-stop for years on end without the need to extract the data in order to free up storage space on the memory card. The logger has an external SD-card where events are stored. This provides an extra layer of data protection and even if events are lost through the GSM communications, a backup version resides in the logger. The ESD loggers are designed to have ultra-low power consumption. This requires complicated software to power down the logger when no measurements are taking place, the logger should then wake up when a rainfall event is registered.

The Electronic Systems Development (ESD) loggers are still in the evaluation phase. Some problems have been identified and corrected. It is anticipated that the first batch will be ready for operational deployment by mid-August.

If there are any tips from the bucket while the unit is busy with any tasks such as sending data with FTP or reading probes the events from the tipping bucket gets logged in the background with an interrupt routine that is coupled to the event input, the date and time of the tip gets logged so the result is the same as the event handler in the main routine, to the user there is no difference. If tips generated at a faster rate than 1 per second, tips will be lost. When the system finishes off recording it logs the events from the interrupt handler to SD card and then shuts down. As soon as the next time alarm or event occurs the records on the SD card are dumped to the GSM ftp file adding them to the other records in sequence like normal. The logger powers up from either a timed alarm or event input from tipping bucket. If any events (tips) happen while the logger is busy with the timed handler and/or busy with FTP of the data these events will not be missed and an interrupt routine will service the events capturing the date and time of the event.

The event data will be added to the next set of records to be written to SD card and FTP file. Event will do the following:

- The event count gets incremented
- SDI12 probe measurements are made
- ADC is read
- Event header data are written
- The data record will be written to the SD card

Two files are written. The one file is fixed file name of glog3.csv and the other file name depends on the day. If it is a new day, the filename will change. If the number of records to FTP to the server has not yet been reached, then the logger will power down till the next wake up. If the number of records to FTP to the server has been reached (set in Configuration: CFG.nr2ftp), the records will be transferred from the SD card glog3.csv file to the FTP file on the GSM and then will be sent to the server with FTP, this adds 50 seconds to the handler. If the sending is not successful then the records will simply accumulate inside the GSM chip until a successful FTP is achieved, this prevents loss of data records due to bad connection or busy network. Note that there is a 1 Meg limit to the accumulation of records inside the FTP file on the GSM chip. Under normal conditions the FTP file should never get anywhere near 1 Meg. After successful or not successful FTP of files, the logger will then power down. If the FTP is not successful, the logger will just FTP the file next time round.

If any events (tips) happen while the logger is busy with the timed handler and/or busy with FTP of the data, these events will not be missed and an interrupt routine will service the events capturing the date and time of the event. The event data will be added to the next set of records to be written to SD card and FTP file.

The logger should be able to perform the following function:

- Automatically transfer data on a configurable time interval through ftp
- Log events from 1 tipping bucket and 3 Stevens Hydro 2 soil moisture digital sensors using the SDI12 protocol
- Rain gauge tip times should be logged individually
- Any analog channels would be a bonus, but not a requirement
- Timing should be kept accurate using a NTP server
- Local data storage on a SD card

2.1.11. Battery and solar panels

Traditional Lead Acid batteries were purchased for this project due to their relative low cost and availability (Figure 2.14). In order to safely charge the batteries, custom regulators (Figure 2.14) that prevent the solar panels (Figure 2.14) from drawing down the batteries were developed.

The ESD loggers are designed to have ultra-low power consumption. This requires complicated software to power down the logger when no measurements are taking place. The logger should then wake up when a rainfall event is registered, or when it has to perform timed operations, like soil-moisture readings. During evaluation it was determined that the first prototypes lost some data on the odd chance that a rainfall event occurred during the time the logger activates the GSM chip.

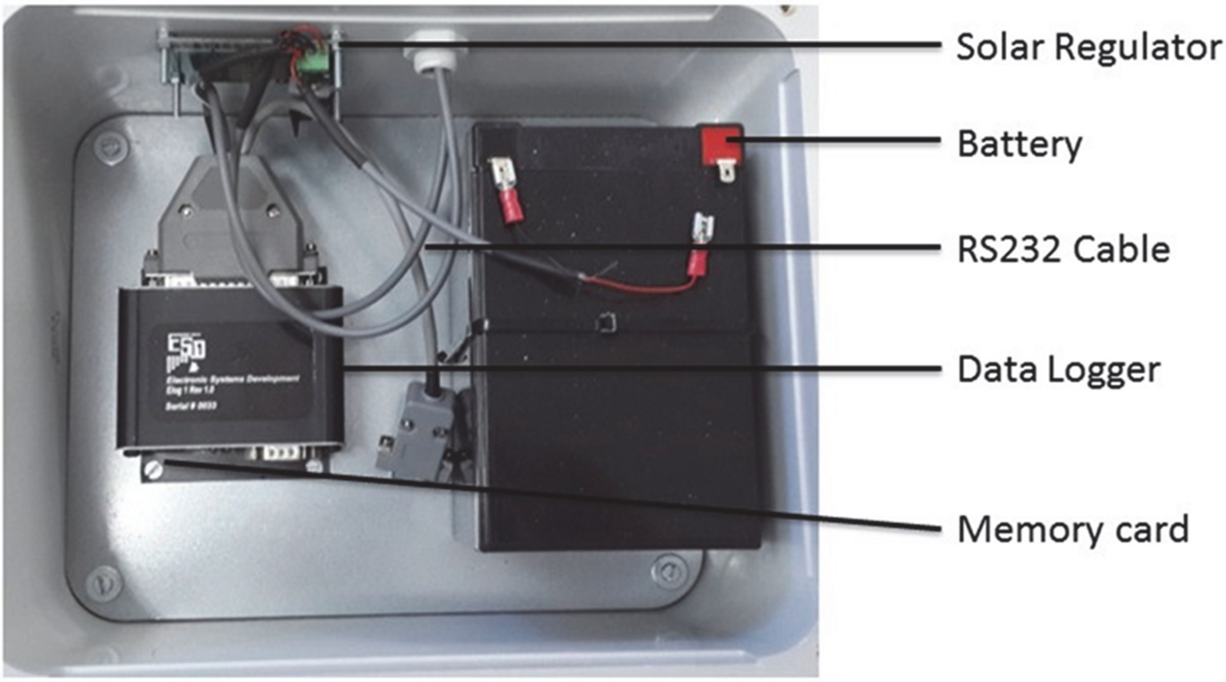


Figure 2.14: An opened enclosure showing the ESD logger and a lead acid battery

2.1.12. OTT parsivel disdrometer

An OTT parsivel disdrometer was deployed in the catchment (Figure 2.15). It is an optical rain gauge that uses cutting edge laser technology to measure rainfall.

A laser beam is used to measure the velocity and diameter of the particle moving through the beam. The lost in voltage is measured and converted into aspects of rainfall such as intensities and amount. A precipitation particle moves through the beam. The loss in voltage received by the receiver due to the shadow of the particle is converted to determine the velocity and diameter.

It is assumed that the Parsivel is the reference instruments, which means it is the most accurate of the instruments used. Therefore, it is very useful for calibration purposes. The Parsivel disdrometer measures particle sizes which can reach up to 25 mm and velocities between 0.2 and 20 m^{s-1} (Battaglia et al., 2009) and has a sampling area of about 54 cm^2. The particles are then categorised into 1024 classes of size and velocity and is displayed on a 32x32 matrix. The resolution of the disdrometer can differ. To eliminate effects such as the sun the Parsivel sends out a pulse signal with the highest resolution being 10s and the lowest being 60 min.

This instrument is useful for radar calibration purposes as it can help us determine the necessary Z-R relationship needed for calibrating the weather radar network

Figure 2.15: The NWU OTT parsivel disdrometer

2.1.13. VAISALA WXT520 weather transmitters

In addition to the traditional tipping bucket rain gauge installed in the Mooi river network four VAISALA Weather Transmitters WXT520 (Figure 2.16) were installed to further extend the weather monitoring capabilities of our network in the catchment.

The VAISALA Weather Transmitter WXT520 is a small and lightweight transmitter that offers six weather parameters in one compact package. WXT520 measures wind speed and direction, precipitation, atmospheric pressure, temperature and relative humidity.

Figure 2.16: The Vaisala WXT520 weather transmitter

2.1.14. Automated weather station

An Automated Weather Station (AWS) was installed in the botanical gardens of the NWU during the sampling period (Figure 2.17)

Figure 2.17: The fully equipped AWS operated by the NWU

2.1.15. Data captured in the Mooi river network

The Mooi river network records rainfall data in a very fine resolution of rainfall (0.2 mm). Every time that 0.2 mm of rain has accumulated in one of the rain gauge buckets a tip event ($ED) is recorded by the data logger. The logger automatically records a timestamp ($TD) twice daily, once at noon and once at midnight (Table 1), just to show that the logger is still working, which is important for data quality control analysis. The following shows an example of the raw data format:

```
Type,Rainfall(mm),,,Date,Time,,,tip difference
$TD,0016,0000000013,2014-11-06,12:00:00,00011,!!
$TD,0016,0000000014,2014-11-07,00:00:00,00011,!!
$TD,0016,0000000015,2014-11-07,12:00:00,00011,!!
$TD,0016,0000000016,2014-11-08,00:00:00,00011,!!
$TD,0016,0000000017,2014-11-08,12:00:00,00011,!!
$ED,0016,0000000018,2014-11-08,17:49:09,00012,!!
$ED,0016,0000000019,2014-11-08,17:50:20,00013,!!
$ED,0016,0000000020,2014-11-08,17:50:43,00014,!!
```

A time series of tip records was logged by the Mooi river network from 01 November 2014 up to present (Figure 2.18). The network did however experience some data losses over this period due to various internal and external factors (Figure 2.18). For example, the Leriana, Westonaria and Welverdiend gauges had some software issues and were offline for about a month each (Figure 2.18). These issues were then fixed during the next site visit. However, the Welverdiend gauge subsequently experienced data losses after the software issues was fixed, but this time it was due to a blockage in the gauge itself which was caused by a spider making a nest inside the funnel of the gauge (Figure 2.18)

(Figure 2.19). The Leriana gauge was stolen during February 2015, which caused a huge loss of data (Figure 2.18). Lastly the Randfontein gauge went offline, also during February 2015 due to the dogs that chewed through the cables relay

There were also other problems detected with the data. In some instances, the issue was not a loss of data, but false data being recorded. An example of this is that occupiers of Site 10, a school in Carletonville, regularly irrigates its grounds (Figure 2.18), and then falsely logged as rainfall. During November 2014 the rain gauge at Site 10 recorded tips of short time duration at regular intervals, when none of its co-located gauges in the network recorded any rainfall (Figure 2.20 and 2.21). It is evident that an unnatural process caused the gauge to tip and in this case it was most likely irrigation that caused the gauge to record the data to the logger (Figure 2.22).

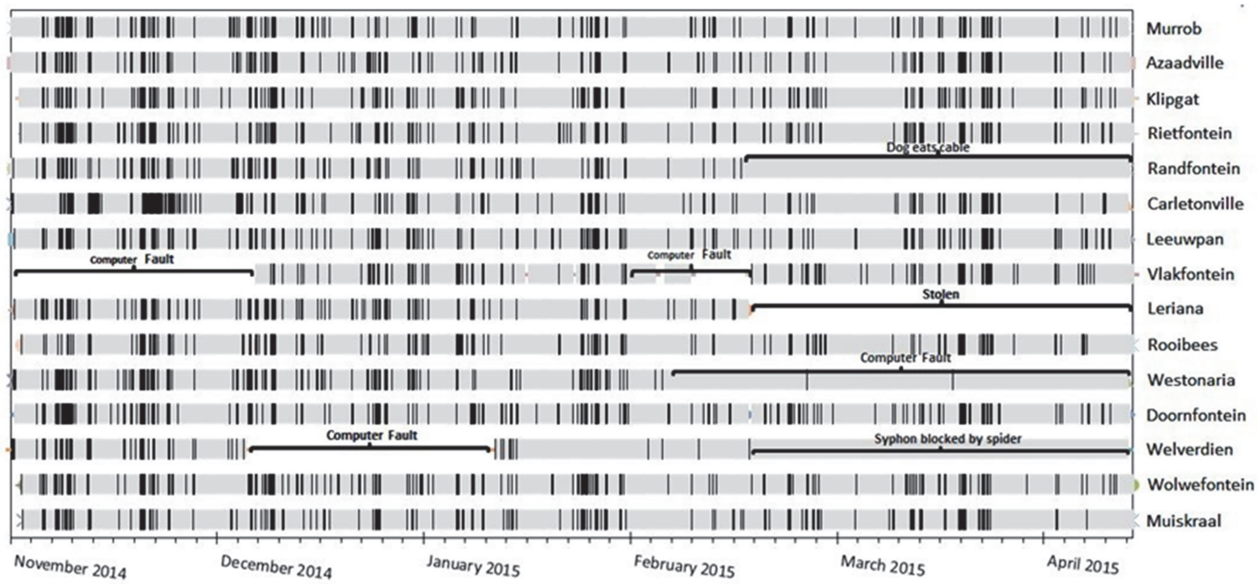


Figure 2.18: Each tip of the rain gauge bucket is represented by a black stripe and the grey area indicates the period of rainfall measurements taken by each rain gauge in the Mooi river network

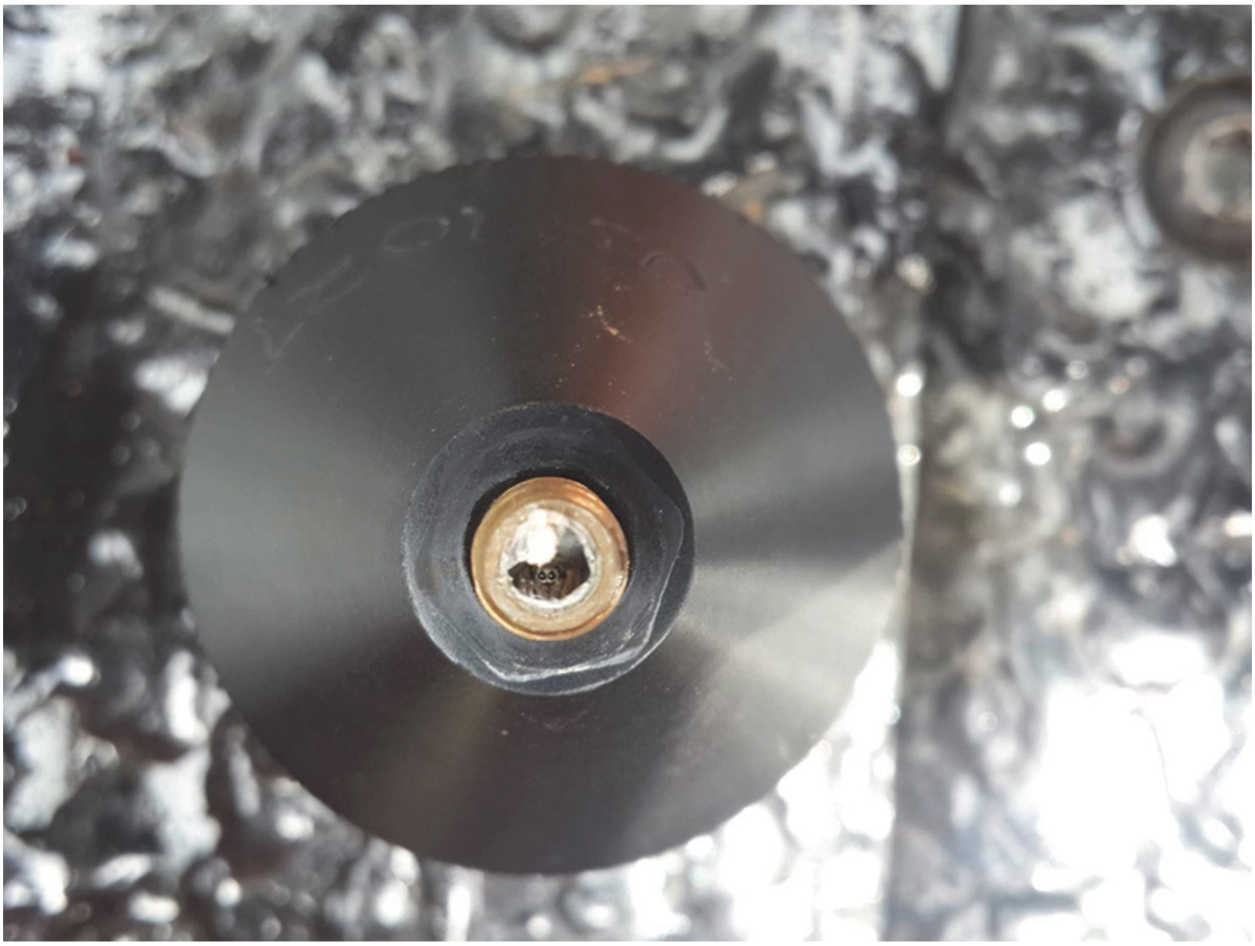


Figure 2.19: Blockage of rain gauge syphon by a spider

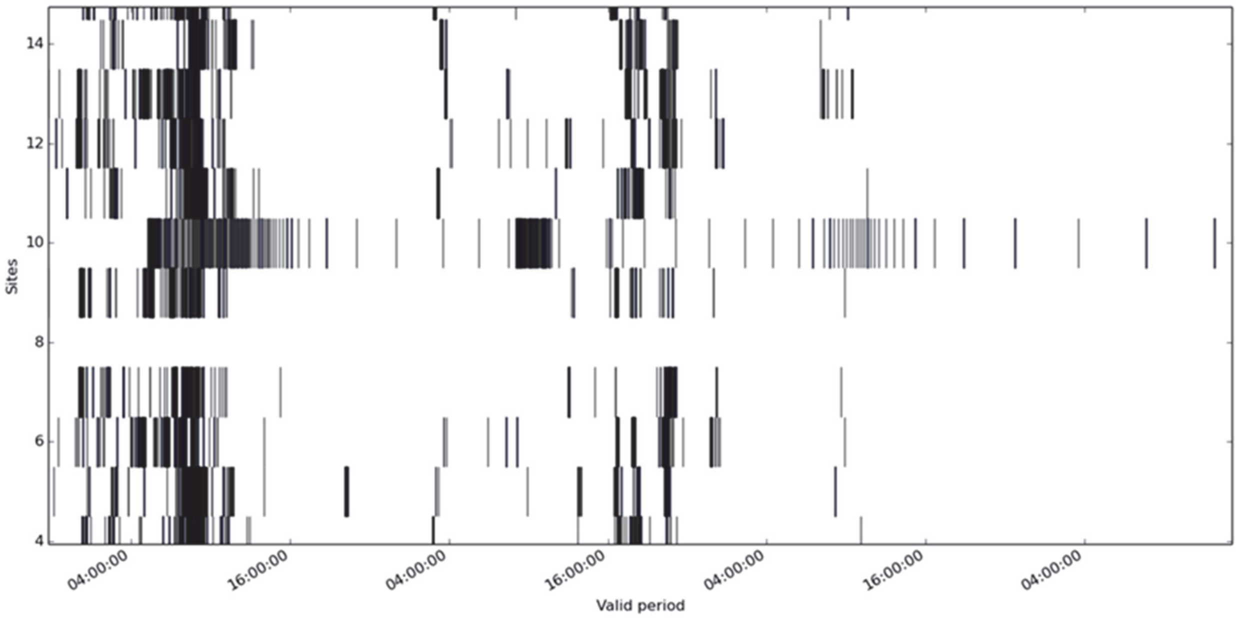


Figure 2.20: Time series of the Mooi river network, gauge tips showing false (unnatural) tips at Site 10 during November 2014

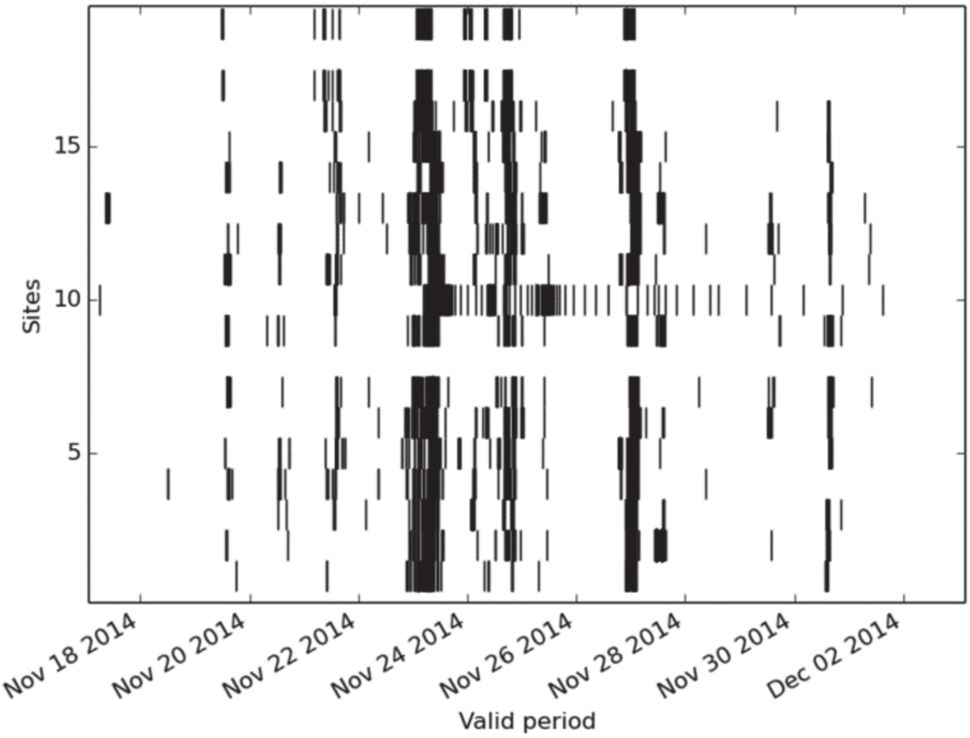


Figure 2.21: Time series of the Mooi river network, gauge tips showing false (unnatural) tips at Site 10 during November 2014

Figure 2.22: The irrigation of a rugby field at Site 10 (Carletonville), causing false data to be recorded by the rain gauge

2.2. The South African Weather Service Radar Network

The history of South-Africa's weather radars started in the early 1970s when the CSIR operated a S-band radar with a 1.1 degree beamwidth about 20 km north of central Johannesburg, this radar was used to study hail on the Highveld (Carte and Held, 1978; Mader, 1979). By the late 80s, the focus of the CSIR changed and the radar was decommissioned. SAWS started acquiring C-band radars from Enterprise Electronic Corporation (EEC), mostly models WSR-88C, for major weather stations across the country. The Water Research Commission (WRC) also funded two radars in the 80s, a C-band EEC and an S-band Russian-built MRL5. The WRC radars were then transferred to SAWS and along with their own fleet slightly modified with a custom built signal processing (Terblanche et al., 1994; Terblanche, 1996) and later networked into a national radar network of ten C-band and one S-band (Terblanche et al., 2001a) using Titan (Dixon and Wiener, 1993). In the mid-2000s, funding was secured to acquire two METEOR 60DX mobile X-band dual polarized and ten METEOR 600S S-band, 1 one of which is dual polarized from Gematronics (now Selex ES). The S-band radars were bought because of observed weakening by the C-band radars in typical Highveld storms, as well as increasing interference from local area network communication on that frequency. Four of the old C-band radars are still operated along with the ten S-band radars.

The current national radar network is plagued by technical problems. A drastic shift towards commercial operation enforced by legislation and dwindling funding has severely limited capacity and resources dedicated to the national weather radar network. This is reminiscent of the shift to market orientated research made by the CSIR that lead to the loss of infrastructure and capacity in the late 80s. SAWS is governed by the South African Weather Service Act, Act no 8 of 2001 (RSA, 2001). In this act, the minister of Environmental Affairs is authorized to promulgate additional regulations regarding the commercial and cost recovery activities of SAWS. Faced with decreasing government subsidy, SAWS has to continuously expand these activities.

The national weather radar network takes up a huge amount of resources and as such is seen as a potential major source of income. In principle, this underscores the importance of this project. However, in practice, tensions arise when choices have to be made between commercial and research goals. Once of these issues is the scan strategy of the weather radar. Commercial interests dictate maximum coverage areas, whereas research interests necessitate high quality data, and therefore high resolution, smaller coverage areas.

The nation weather radar network is a world class asset with enormous potential to provide real-time data to a wide variety of stakeholders. It can be used for decision support in the commercial sector, help manage water resources, stimulate research to name a few. Although some of these opportunities are being capitalized on, we are nowhere near using the infrastructure to its full potential. The network is grossly underfunded and understaffed. SAWS has lost a lot of its skilled scientists, technicians and engineers. A huge effort, as well as decisive political will is needed to turn the tide.

One of the aims of this project is to help build capacity in this field to improve the situation.

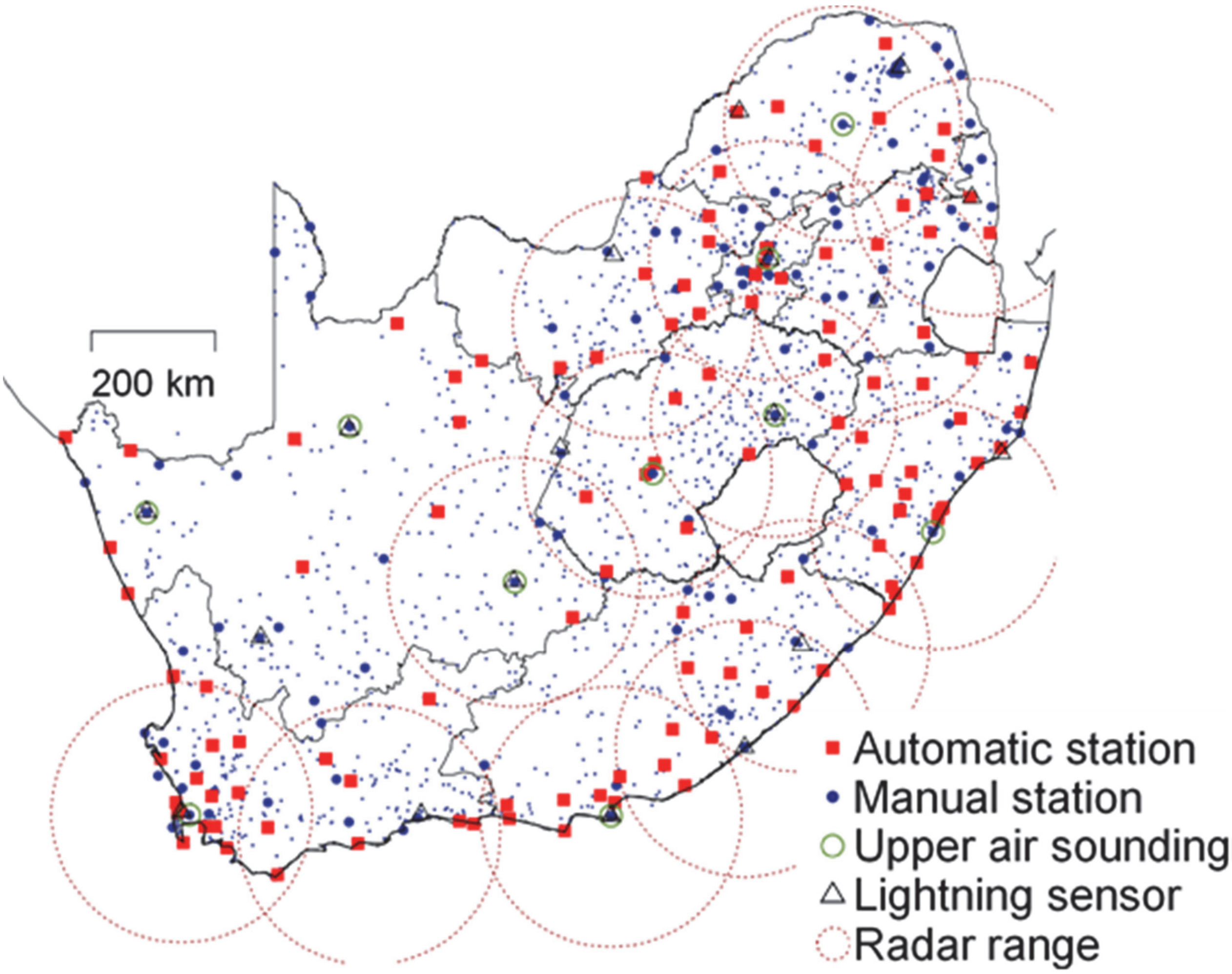


Figure 2.23: The principle components of the SAWS observation network. A 200 km range ring is drawn around each of the radars.

2.2.1. Overview of the SAWS radar network

The current radar network managed by SAWS consist of 14 radars that are being run used operationally (Figure 2.24 and Table 2.1). Another 2 two mobile X-band radars have not been deployed. The network covers the largest part of the eastern portions of eastern South Africa. This includes the most highly populated areas as well as areas with the highest mean annual rainfall. While the radars are being operated at ranges up to 300 km, for rainfall purposes, the most useful ranges should not exceed 200 km. The optimal distance from a radar for rainfall estimation lies between 70 and 150 km.

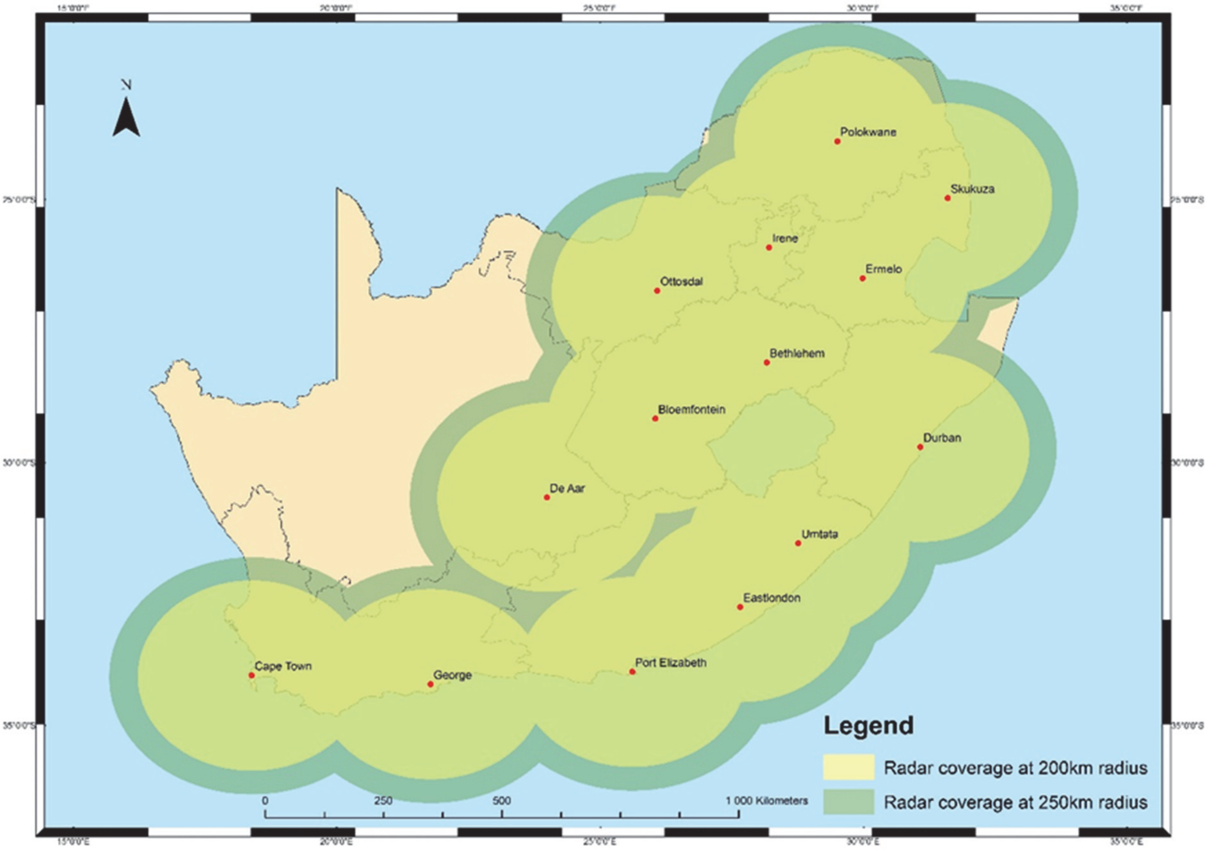


Figure 2.24: The SAWS radar network.

Table 2.1: Key parameters of the national radar network currently in operation. The height is given above mean sea level, the beam refers to approximate beam width in degrees, and the band is the frequency of the radar

Radar	Descriptor	Latitude	Longitude	Height	Beam	Band
Cape Town	FACTC	-34.05406	18.38532	905	1	C
Port Elizabeth	FAPEC	-33.98466	25.61075	75	1	C
East London	FAELS	-32.75567	27.66160	603	1	S
Durban	FADNS	-29.70723	31.08155	137	1	S
Umtata	FAUTS	-31.53714	28.76446	857	1	S
De Aar	FADYC	-30.66476	23.99267	1284	1.5	C
Bethlehem	FABLS	-29.16627	26.05105	1556	1	S
Bloemfontein	FABMS	-28.09837	28.16324	1722	1	S
Ermelo	FAEOS	-26.49803	29.98406	1773	1	S
Ottosdal	FAOTS	-26.73519	26.08766	1514	1	S
Irene	FAIRS	-25.91193	28.21072	1532	1	S
Skukuza	FASZS	-24.97395	31.60064	299	2	S
Polokwane	FAPPS	-23.89357	29.50569	1396	1	S
George	FAGGS	-34.21950	21.78265	236	1	S

2.2.2. Data availability of the SAWS radar network

SAWS has only a handful of skilled technicians and scientists dedicated to the radar network. Combined with a limited budget, results in data not always adequate for research or rainfall estimation purposes. Many of the radars suffer from technical problems and limited spare parts and as such only about 50% of data is available (Figure 2.25). The Irene radar (Figure 2.26) had the best data availability for the study period.

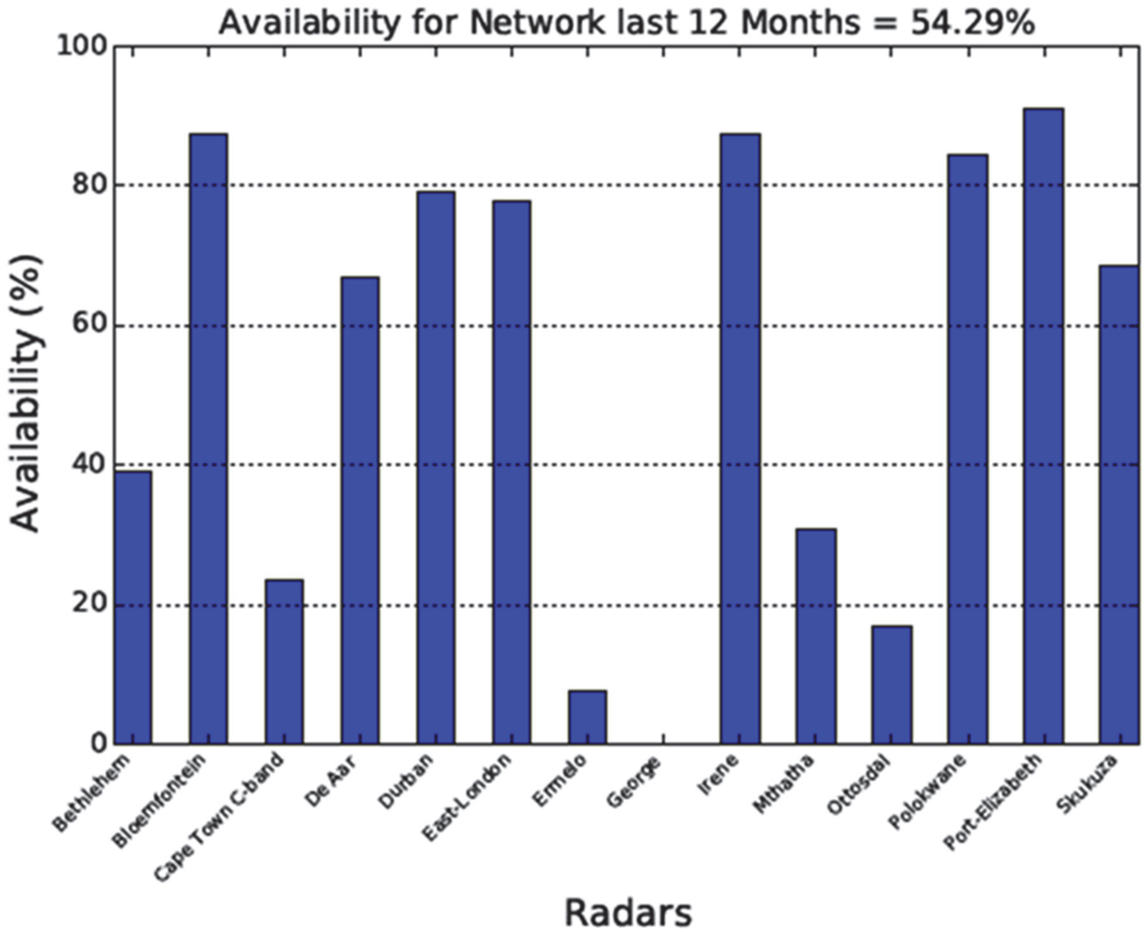


Figure 2.25: Data availability for radars in the national network during the project period

Figure 2.26: The Irene radar

2.2.3. Calibrating the Bethlehem radar

The S-band Bethlehem radar was calibrated in the first week of July. After some technical and communication difficulties in May and June have been fixed, the radar is currently operating within specifications

2.2.4. Finding a compromise scan strategy

After detailed analysis, a compromised scan strategy was adopted by SAWS to ensure higher quality data for the radar network. The range of the radars have been limited to 200 km in the process

Table 2.2: Scan strategies used by SAWS for their Irene and Bethlehem radars

Parameter	300 km Scan Strategy	200 km Scan Strategy
Elevation Steps	30, 22, 16.8, 12.2, 9.9, 7.9, 6.2, 4.7, 3.4, 2.3, 1.3, 0.5	
Unambiguous velocity	50-125 m/s	14-80 m/s
Samples	18-22	31-43
Duration	354 seconds	357 seconds
Bin Resolution	500 m	
Pulse Duration	0.85-1.67	0.85-1.67
PRF	500/400	750/600
Antenna Speed	10-30 °/s	10-32 °/s

2.2.5. C vs S-band radar comparisons

A study to compare C and S-band radar performance have also been undertaken (Figure 2.27). The Irene C-band was operated together with the S-band for the first quarter of 2010. This will provide better insight into how the new S-band measurements will relate to the C-band data record that spans the last decade.

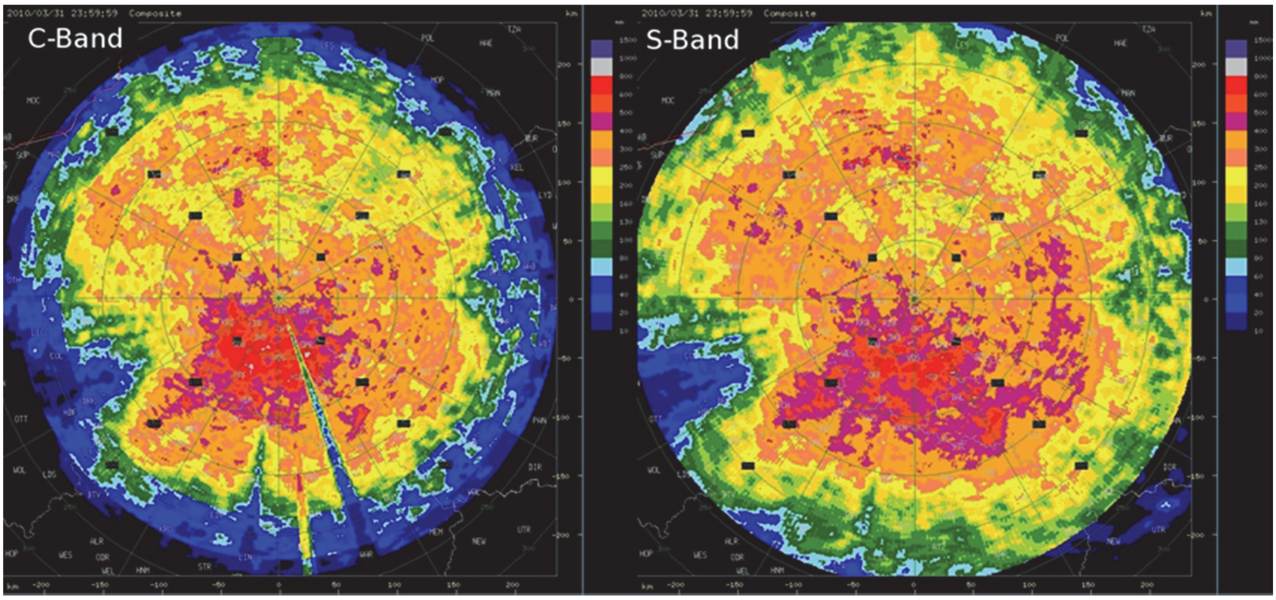


Figure 2.27: A comparison of the old C-band Irene precipitation estimates with the new S-band radar for a 3-month period ending March 2010

2.2.6. Technical problems with the Bethlehem radar

Technical problems with the new S-band radar close to Bethlehem persists. A microwave link is used to communicate between the radar and the Bethlehem weather office. This link has had continued disruption in the past year.

The new radar also experienced an unexpected magnetron failure. This has led to some data loss during July. The problem has been fixed and the radar is operational again. A full calibration was conducted on the Bethlehem radar after the magnetron was replaced. The performance of the Bethlehem radar between March 2011 and June 2012 is shown in Figure 2.28. The Radar became operational in June after having technical difficulties from the middle of May.

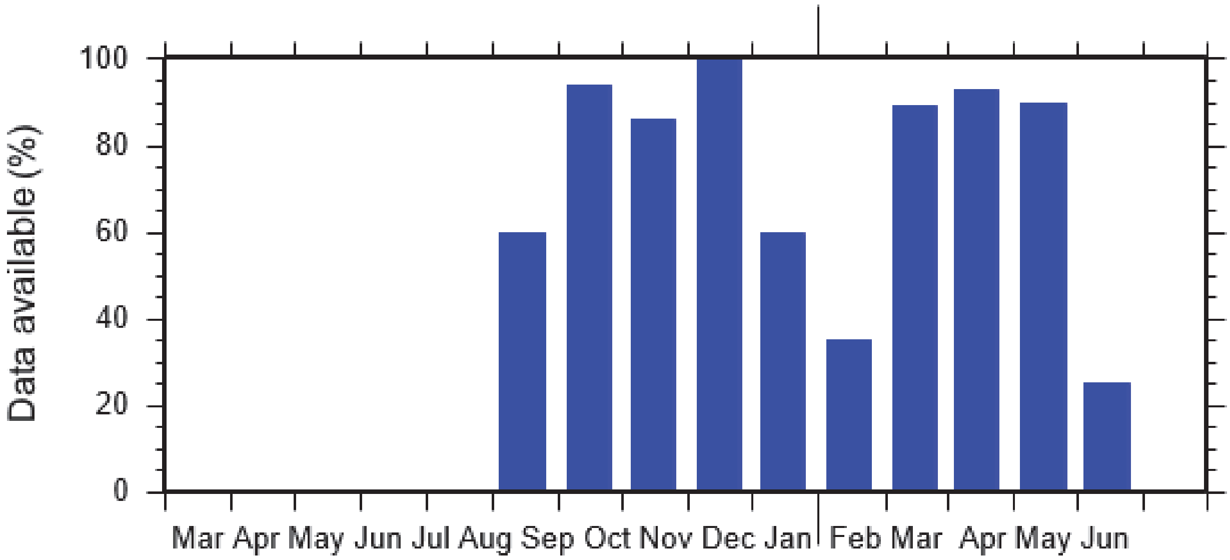


Figure 2.28: Data availability of the Bethlehem radar between March 2011 and June 2012

The methodology of the project is continually being revised as operational requirements change. The importance and challenges of finding the right logger/modem combination was not anticipated at the start of the project. Some of the plans will be outlined in the following section.

2.3. The NWU Lekwena C-band Weather Radar

The North-West University (NWU), with support from the Water Research Commission (WRC), acquired an old WSR-74C radar to provide a research plat- form in order to build capacity and train engineers and scientists in South Africa. This work holds additional relevance to water research in South Africa as it aims to provide real-time research grade data to the scientific community. It further demonstrates the potential of the four C-band, as well as the six decommissioned SAWS C-band radars currently in storage to be re-engineered and redeployed in the national weather radar network.

The NWU Lekwena radar is a 1974 C-band weather surveillance radar manufactured by Enterprise Electronics Corporation (EEC). Also known as an EEC-WSR74C radar. The radar originally operated in Cotulla, Texas where it stood for the about 30 years. Apart from the smaller antenna, the specification of the radar is similar to that of the four C-band radars still in operation and the six ones decommissioned by SAWS.

2.3.1. Site Selection

The site selection consists of two criteria types: 1) strategic and 2) logistic. The strategic criteria is determined by the meteorological objects observed, the purpose of the radar and who will benefit from it. The logistics criteria focuses on the feasibility of the project, installation requirements available infrastructure and local political considerations (Dalezios et al., 1990; Domenikiotis et al., 2010).

For most weather radars its primary use will be to aid a weather network with real-time, high-resolution rainfall estimates over a large area (NOAA 2010). This will require a low scan elevation for the highest resolution over long distances (Dalezios, Papamanolis and Linardis 1990). To ensure the highest data quality the horizon should be unobscured as far as possible (Dombai 2010). However, if the purpose is more scientific related such as studying hail storms, cloud seeding, ground clutter or high flash flood regions it is likely that the radar will be situated in a non-ideal location where these phenomena occurs more frequently (Domenikiotis et al., 2010). An example is the research radar part of the Bethlehem Precipitation Research Project (BPRP) used to monitor cloud seeding effects (Terblanche et al., 1994). The Bethlehem region is not the ideal site for radars because of the Drakensberg mountain range toward Lesotho with a maximum altitude of 3000 m above sea level. It was known that there will be problems with ground clutter, yet Bethlehem was deliberately chosen because of its advantages to the BPRP study.

The site selection is largely dependent on the meteorological purpose of the radar, but equally important is the logistical criteria including the infrastructure, power supply, security, access, communication link and licensing conditions (NOAA 2010). The infrastructure mainly consists of two structures 1) the building containing the radar system and 2) the antenna platform. The radar building houses the radars transmitter/receiver, antenna control unit, and signal processing and calibration equipment as the computers. A good ventilation unit is compulsory as the transmitter generates heat. The second infrastructure is the antenna platform, this is usually elevated above the transmitter/receiver unit and it is preferred that the platform is elevated above buildings or trees close to the site to minimize ground clutter. A radar will generally be located on the top of a peak subjected to harsh conditions. These conditions include heavy rain, hail, wind and constant sun. Radars are designed to operate for years on end therefore require a solid and stable platform. Lower scan elevations will produce a higher resolution but increases the chance of ground clutter (Buyukbas et al., 2005). Clutter creates false data, essentially blocking a coverage area. A method to overcome this problem is to raise the antennas height. Though it will decrease the clutter, a higher tower will increase the lobbing effect therefore needing a much stronger structure (Domenikiotis, Dalezios and Faraslis 2010). It becomes a trade-off between higher resolution, constant clutter and cost. The Lekwena radar blockage due to topography is shown in Figure 2.29.

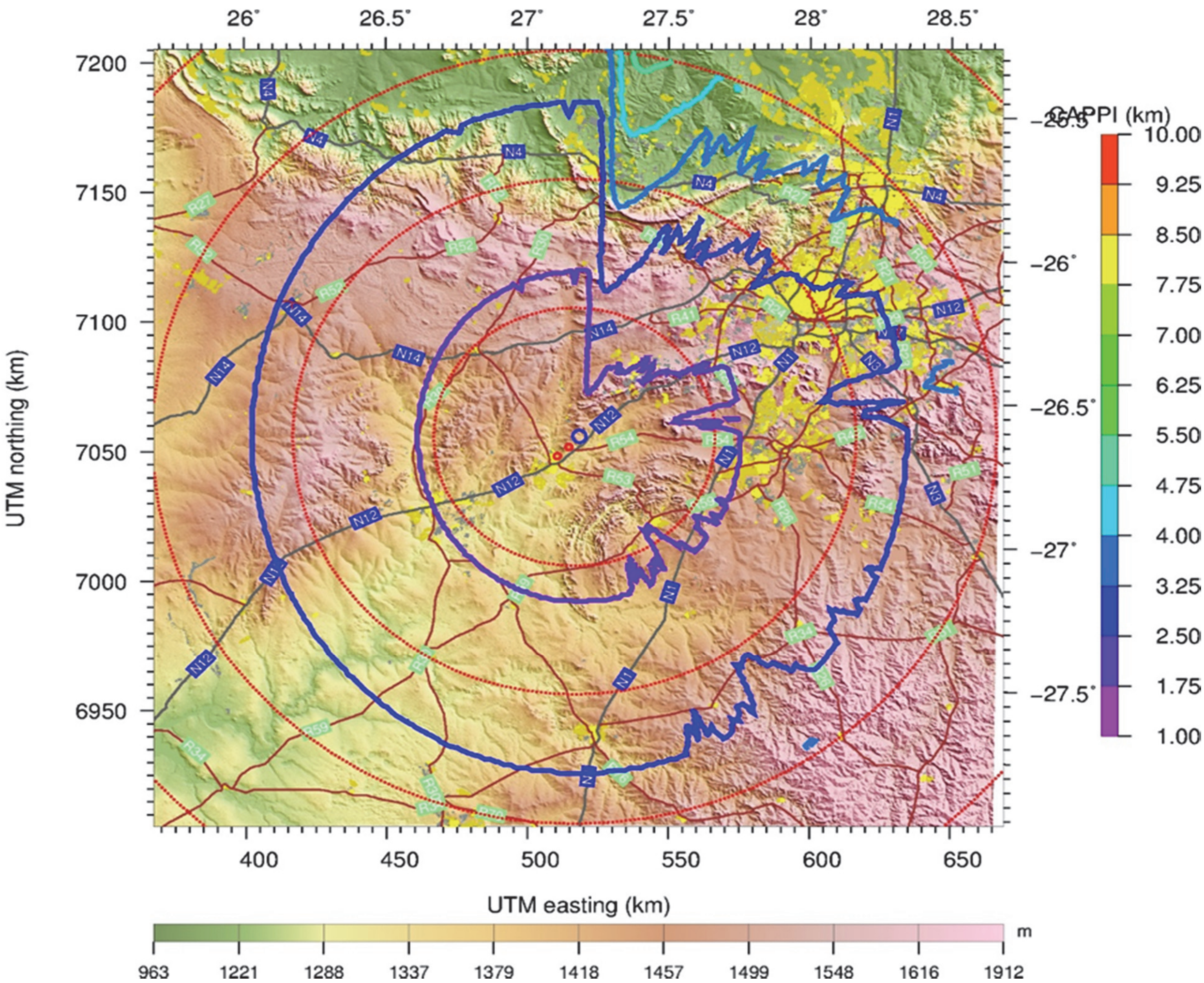


Figure 2.29: A beam propagation analysis of the current NWU Lekwena radar site

The site preparation and radar installation is an expensive and time consuming process. It is imperative that the correct site is chosen before proceeding with the physical installation. Once a possible region or mountain range has been identified, an estimation of the data quality can be determined through software models. These models use local topography data to determine the lowest useable elevation scan for a certain range (Dombai 2010). There are multiple software packages already available such as ArcView, ArcGIS, FTAY and RMDS (Baltas and Mimikou 2002, Shipley et al., 2006). Most of these models are based on the Geographic Information System (GIS) database.

Radars are generally operational for long periods of time requiring a constant and stable power supply with at least 20A at 220V or 4.4 KVA (Domenikiotis, Dalezios and Faraslis 2010).

The receiver uses very sensitive components and any power fluctuations may alter the data or damage these components. It is recommended to use an inline filter system as an uninterrupted power supply (UPS) with a backup generator supporting the UPS in case of a power outage. Once the UPS shuts down most radars will not automatically restart. The backup generator must not be used in the same building as the radar unit.

Security is always a concern, not only to keep the equipment safe but protect individuals from climbing on top of the antenna platform, especially while the radar transmits. Modern weather radars can transmit up to 1 MW pulses which can have negative effects if exposed for long periods of time (Michaelson 1974).

Lightning is one of the most destructive events for electrical equipment. A radar makes use of very sensitive components and the slightest voltage spike can cause major damage. It is therefore important to have a good grounding network providing a low impedance ground path. The grounding is typically made from a copper network beneath the ground to provide a maximum resistance. It is important to connect all metal objects on the same analog ground (Buyukbas, Sireci and Macit 2005). Lightning is drawn to the net charge of a site due to the potential difference between the two points. One method to prevent lightning striking the radar is to minimize the radars potential to the earths (Kasemir 1960).

It is well known that C-band weather radars are prone to microwave interference with communication systems in close proximity. There is a real concern as the need for wireless internet operating at 5 GHz keeps increasing. Regulations prohibits Radio Local Area Networks (RLAN) from operating on the same frequency but it is difficult to implement such a rule. Modern communication systems consist of Dynamic Frequency Selection (DFS) which allows the software to only use frequency bands that are not used. Unfortunately most users are unfamiliar with this function and its interference with weather radars (Buyukbas, Sireci, Hazer, Temir, Macit and Gecer 2006, Joe et al., 2005). Being aware of this problem precautions can be taken to determine if a site is electromagnetic compatible before proceeding with the installation. Radars require routine inspection, maintenance and the generator requires refueling, it is therefore necessary to have access to the site with at least a car or preferable small truck. A communication link with the site is always preferred so that radar can be controlled and data accessed remotely

When considering a site, the following points must be kept in mind:

- The site must not be close to a residential area due to the continuous high power pulses transmitting.
- High enough so there is a least amount of obstructions in front the pulse path. This includes natural and man-made structures as mountain peaks or towers.
- The site must be accessible by a car for the installation and maintenance of the radar.
- A local power supply to provide constant power.
- Area big enough to pour a foundation on which the antenna platform will be fixed.
- Fire prevention method if required.

- Communication access to remotely control the radar.
- Safety and limited access to the radar site and equipment.

There are software programs available to help determine what the natural obstructions of a specific site is. An example is the Radar Simulation Tool developed by the CSIR and the South African Air Force (SAAF). A few sites in the area of Gauteng and Potchefstroom were identified as possible radar sites, to further evaluate these sites Mr. Roelof Burger, a researcher at the North-West University, wrote his own program to determine the minimum CAPPI (constant altitude plan position indicator) figure for each site. The CAPPI shows the natural obstructions that the transmitted pulses might encounter. This is illustrated through circles around the site with a specific colour.

2.3.2. Logistics of the NWU Lekwena radar

The radar is operated from an air-cooled container with the antenna placed on a platform directly above the radar. To ensure that the radar and antenna moves the minimum amount a concrete foundation is was poured. The container was moved to the site and a steel platform was built over the container (Figure 2.30).

The radar needs a constant and reliable power source since the radar operates continuously for weeks on end. The biggest problem is that the closest power source is at the bottom of the hill, a total distance of 600 m away. Alternative energy as solar power and batteries were considered but after some research it became obvious that for this amount of power the price would far exceed R1.5 Million. The solution was to dig a trench all the way to the power source and use an armored power cable, using a cable also came with another challenge. A high current sent over a great distance has a high voltage drop. According to manufactured specifications a cable must have a maximum of 5% voltage drop over the entire distance. To allow for a maximum of 5% voltage drop either a large cable must be used or the current has to be lowered. A bigger cable is exponentially more expensive than a smaller one. Else the current needs to be lowered through purchasing two transformers. The first transformer is used to boost the voltage at the supply to 1000V, decreasing the input current. This allowed the cable to be much smaller, saving cost. At the receiving side the second transformer was used to step-down the 1000V to the original voltage. With the decreased current, a much smaller cable was used, saving money.

While the power was connected a back-generator was purchased and installed through by a qualified electrician. The generator was used as a primary power supply until the main power was connected, there after the generator is was only be used as a back-up supply when needed.

There are still a few key installations required for the communication link, but the radar is fully operational and producing valuable meteorological data. The radar is close to 40 years old, so there are some technical problems. Some of the electronic units are not working as expected due to internal losses and decrease of efficiency over the years. These units will not cause the radar to stop working but it will influence the accuracy and reliability. Some of the components internal circuits are obsolete thus an alternative component will have to be sourced or the complete units will have to be replaced. Currently a problem has occurred with the AFC (Automatic Frequency Control) unit but a solution is being explored. The figure below is an example of data collected from the radar.

One shortcoming is a communication network between the radar and North-West University. This network will allow the user to monitor and control the radar remotely. Also the data collected can be sent through the network to any location needed. The proposed network is to use a WIFI connection with a possible bridge connection in between.

Figure 2.30: A mosaic of the NWU Lekwena radar installation.

2.3.3. Calibration and performance of the NWU Lekwena radar

Routine maintenance, inspection and calibrations are important to ensure accurate quantitative estimations of precipitation (Thorndahl and Rasmussen 2012). Calibrating a radar consist of three aspects, calibrating the 1) transmitter, 2) receiver and 3) antenna.

The maximum range of radar is related to the peak output power of the transmitter (Richards, Scheer and Holm 2010). As the output power decreases so will the received echoes de- crease in amplitude, therefore under estimating rainfall reflectivity. During the calibration the following parameters have to be constantly measured for any fluctuations: 1) pulse width, 2) pulse repetition frequency, 3) duty cycle, 4) peak power and 5) voltage standing wave ratio (Buyukbas, Sireci, Hazer, Temir, Macit and Gecer 2006). Each calibration process will shortly be explained. The calibration equipment used are shown in Table 2.3.

Table 2.3: Calibration equipment of the Lekwena radar

Measurement	Equipment Required	Description
Peak power	Power meter	HP Hewlett-Packard 435A
	Power meter sensor	HP Hewlett-Packard 8483A
	Oscilloscope	Tektronix TDS 1001C-EDU
PRF	Power meter	HP Hewlett-Packard 435A
PW	Power meter sensor	HP Hewlett-Packard 8483A
DC	Oscilloscope	Tektronix TDS 1001C-EDU
	50 Load terminator	
	Crystal detector	
VSWR	Power meter	HP Hewlett-Packard 435A
	Power meter sensor	HP Hewlett-Packard 8483A
MDS	Power meter	HP Hewlett-Packard 435A
	Power meter sensor	HP Hewlett-Packard 8483A
	Oscilloscope	Tektronix TDS 1001C-EDU
	Signal generator	HP 8684B Hewlett-Packard
Response curve	Oscilloscope	Tektronix TDS 1001C-EDU
	Signal generator	HP 8684B Hewlett-Packard

2.3.4. Pulse width (PW)

The pulse width is the duration of the pulse measured from the start the finish.

1. Position the antenna away from any constant echoes and switch the antenna control to OPERATE
2. Connect the 20 DB attenuator to the forward port on the bi-directional coupler at the transmitter followed with a crystal detector afterwards
3. Using a BNC T connector, the one end is connected to the crystal detector, the

other end to a 50 termination load and the middle to oscilloscope port. The trigger from the transmitter can also be used to externally trigger the oscilloscope.

4. Start radiating and the adjust oscilloscope until a clear pulse can be seen.

5. The pulse width is measure at 70% of the pulse amplitude or also known as the -3 DB value.

2.3.5. Pulse repetition frequency (PRF)

The PRF is the amount of pulses sent out per second.

1. Readjust the oscilloscope to see at least two pulses.

2. Measure the time from the start of one pulse to the next, also known as the pulse repetition time (PRT).

The PRF is calculated through: $$PRF = \frac{1}{PRT} \quad (2.1)$$

2.3.6. Duty cycle (DC)

The (DC) in DB value is determined as follow: $$DC = 10\, log \frac{1}{PW * PRF} \quad (2.2)$$

2.3.7. Peak Power

The peak power measurement is important to ensure the operation status of the transmitter and accurate data analysis.

1. Connect a 20 DB attenuator to the forward port on the bi-directional coupler at the transmitter.

2. Connect the power meter to the attenuator, start radiating and record the measurement.

The peak power is calculated as follow:

$$Peak\ Power = Attenuator + Duty\ Cycle + Coupler\ Attenuation + Power\ Measurement \quad (2.3)$$

2.3.8. Voltage standing wave ratio (VSWR)

As energy propagates through a transmission line some energy gets reflected back to the transmitter known as Voltage Standing Wave Ratio (VSWR), VSWR can give an indication of a defective waveguide, the condition of the antenna or any mismatch impedance between the transmitter/ receiver and the antenna. VSWR is expressed as a ratio between the transmitted and reflected power. A VSWR of 1:1 indicates that no power is reflected back to the transmitter, an ideal situation but rarely ever obtained. For an accurate VSWR reading the measurement should be taken at point of interest, for example the antenna location. Most radars will have two bidirectional couplers, one located at the transmitter and the second one at the antenna (VSWR).

The VSWR is determined as follow:

1. Position the antenna away from any constant echoes.

2. Connect the power meter through a 20 DB attenuator on the reverse power port on the bi-directional coupler and start radiating at full power.

3. Record the power measurement and switch radiating off.

4. Reposition the 20 DB attenuator and power meter to the forward power port on the bi-directional coupler and start radiating at full power.

5. Record the power measurement and switch radiating off.

The total forward power is calculated adding the DB value of the attenuator, bi-directional coupler attenuation and measurement on the power meter. The reverse power is calculated in the same manner. A relative good VSWR for a weather radar has a ratio of less than 1:1.1 or return loss of between 26 and 40 DB. Return loss is the difference between the forward and reverse power. The following formula can be used to calculate the VSWR:

$$VSWR = \frac{1 + 10\frac{-Return\ loss}{20}}{1 - 10\frac{-Return\ loss}{20}} \tag{2.4}$$

The radar receives signal over a wide range from -110 to 0 dBm (Bykbas, Sireci, Hazer, Temir, Macit and Gecer 2006). With such a wide range the receiver makes use of a logarithmic scale to better represent the data. The logarithmic data is used to establish a correlation between the received signal measure in dB and rainfall rate, also known as a Z-R relationship (Rinehart 1997). The Z-R relationship is used to present 0.004 to 150 mm/h rainfall rate generally divided into 14 levels (Teschl et al., 2007). The receiver uses a response curve to correspond the received signal from the receiver to a DBZ value used in the Z-R relationship. Calibrating the receiver mainly consist of ensuring that the response curve is still accurate. This includes determining the minimum detectable signal (MDS) (Bykbas, Sireci, Hazer, Temir, Macit and Gecer 2006).

The minimum detectable signal is the smallest signal or reflectivity that the receiver can use to distinguish between data and noise. The following process is used to determine the MDS:

1. Always ensure the antenna control is set SAFE before starting with any receiver calibrations.

2. Ensure the radar is switched to local control and AFC/MFC to MFC

3. Connect the oscilloscope to the video output of the radar and the trigger to both the oscilloscope and modulator for sync.

4. Set signal generator to external trigger mode. Always decrease the signal generator output power before connecting or removing the cable.

5. Connect the signal generator to the forward port on the bi-directional coupler.

6. The modulator is connected to the signal generator external trigger and setup as follow: external sync, delay with approximately 400 s and pulse width of 100 s.

7. Increase the signal generator output power until a clear pulse can be seen on the oscilloscope.

8. Use the MFC adjustable frequency knob to peak the pulse in amplitude.

9. Decrease the signal generator output power until the pulse until only 50% of the pulse amplitude is above the noise level. Record the signal output power for further calculations.

The receiver sensitivity or MDS is determined through adding the signal generator output power recorded in step 4, any cable losses, bidirectional coupler attenuation and waveguide loss to the pedestal together.

Calibrating the response curve repeat the setup from 1 to 8. The response curve consists of different signal power increments representing a certain dBz value. The increments are determined by the type of receiver software used. The following steps are followed to complete the receiver calibration:

1. Set the signal generator power to the first increment according to the software.

2. Use the MFC adjustable frequency knob to peak the pulse measured on the oscilloscope.

3. Record the measurement with the receiver software.

4. Repeat 6 and 7 for every increment required.

2.3.9. Calibrating the antenna

The third calibration is the antenna's alignment to true north. If the azimuth alignment is out by only 1 degree, over 150 km a cloud would be misplaced by 2.6 km. There are two methods used to check the radars alignment, a fixed echo or through tracking the sun. The first method is used with a known constant echo as a building, mountain, tower or metal-coated sphere balloon. These echoes have a specific elevation and azimuth. To test the radars alignment, the antenna is directed towards a known echo. If the radar receives an echo, the radar is still calibrated (ANON 2014).

The second method and more commonly used is to mathematically determine the suns position relevant to the radar. The receiver of the radar is able to pick up the suns radiation if the antenna is pointing directly at the sun. This phenomenon is also known as a solar spike and occurs mostly during early morning or late afternoon. Modern software packages include a sun tracking calibration tools. It’s a quick and effective method to check or recalibrate the antennas position (ANON 2014, Huuskonen and Holleman 2007). Most antenna pedestals have an upper and lower elevation limit.

Setting the limit switches

The EEC C-band pedestal have a mechanical stopper and electronic switches preventing the antenna from moving out of its elevations margin. The mechanical stopper must only be used as a last resort since the forceful stop can damage internal components as the motors or gearbox. The pedestal has two switches, inner switch (3S2A) used for the lower limit and the outer switch (3S2B) for the upper limit. Each switch consist of two adjustment screws A and B. The installation of the limit switches on a WASR74C radar is as follow:

Always ensure the antenna control is set SAFE before entering the radome area.

1. Remove the elevation cover and manually lower the antenna to the minimum elevation required.
2. Connect a multimeter testing for continuity on the inner switch between the normally open (N.O.) and common.
3. Loosen the clamps screw A on the lower switch, turn the adjustment screw fully clockwise and fasten the screw again.
4. Repeat the same procedure (4) for B but only turn the adjustment screw until the connection between the N.O. and common is a closed connection and fasten the screw.
5. Manually raise the antenna to the upper elevation and connect the multimeter between the N.O. and Common terminal of the outer switch.
6. Loosen the clamps screw B on the outer switch, turn the adjustment screw fully counter clockwise and fasten the screw again.
7. Repeat the same procedure (7) for A but only turn the adjustment screw until the connection between the N.O. and common is a closed connection and fasten the screw.
8. Manually lower and raise the antenna to check the limit switch through measuring the connection between the N.O. and common terminal on each switch. Replace the elevation cover and switch antenna control back to OPERATE.

The limiting switches should always be set with a broader span than specified in the scan strategy to prevent the antenna from stopping premature. It is suggested to set the lower limit to -1° and the upper to 60° just before the mechanical stop.

2.3.10. Technical specifications

Table 2.4: Technical specifications of the NWU Lekwena radar

Radar Transmitter & Receiver	**Symbol**	**Specifications**
Frequency band		C-Band
Magnetron frequency	f	5620 MHz
Output power [dB]	p_t	81 dBm
Output power [W]	p_t	125 kW
Duty cycle	DC	31.03 dB
Pulse width	PW	3 us
Pulse repetition frequency	PRF	263
Pulse repetition time	PRT	3.80 ms
Pulse length	h	5.33 cm
Minimum detectable signal	MDS	-108,8 dBm
Maximum range	r	200 km
Dielectric constant	K	0.93
Voltage standing wave ratio		1:1,1
Antenna	**Symbol**	**Specification**
Antenna diameter	d	2,4 m
Antenna gain	g	40 dB
Beam width horizontal	θ	1.65°
Beam width vertical	θ	1.65°
Height from ground		4.6 m
Height above sea level		1516.6 m

Antenna	Symbol	Specification
Rotation speed		30° s-1
Upper EL limit		35°
Lower EL limit		1.8°
Time per volume scan		3 min 23 sec
Software	**Symbol**	**Specification**
Signal processor		RDAS2K
Processing software		TITAN
Remote communication access		2,4 GHz point-to-point connection

2.3.11. Upgrading the NWU Lekwena radar transmitter

To fully utilize this radar as a top of the line research grade instrument the radar will be re-engineered and upgraded in three stages, the transmitter, receiver and antenna unit, with the specifications shown in table 2.5

Once the radar is upgraded it will be one of the best research radars in Africa, capable of measuring dual-polarization with Doppler Effect over a 200 km radius. The NWU decided to purchase an older radar instead of a new one with the intent to re-engineer the radar. The first stage consisted of replacing the original transmitter unit with a solid-state transmitter designed by Pulse system Inc., this was completed in March 2015 without complications. The original transmitter still made use of technology developed in the early 1970s therefore one of the major constraints were that many of the internal components have become obsolete and all the parameters were fixed. The components that are still available are difficult to obtain and comes with a high price, when a component as small as a relay switch brakes, the radar will be offline until it is replaced or modified to fit a custom replacement. The table below shows the difference before and after the transmitter upgrade.

From the table 2.5 it is clear that the transmitter upgrade has multiple benefits to the radar system. The maximum peak power is increased with 46%, expanding the effective range. The duty cycle, pulse repetition frequency (PRF) and pulse width can all be changed according to user requirements. It is very important that the transmitter can cooperate with any receiver unit and support Doppler capability. Figure 2.30 and 2.31 shows the upgrade process of the transmitter.

The second stage will consist of replacing the receiver unit with a Pentek-based DRX unit capable of dual-polarization and Doppler Effect. This receiver was designed by the National Centre for Atmospheric Research (NCAR) in Boulder, Colorado and is currently used by USA’s top rated research radars. It is a state-of-the-art receiver that can be assembled using off-the-shelf products making it easier to build and maintain. The NWU is working in close collaboration with NCAR to design such a receiver unit for the radar system.

The third stage will consist of replacing the antenna and its control system with a newer model. The antenna is a key component in the data quality since the beam width determines the resolution of the radar. The current antenna is a 2.4 m parabolic dish with a beam width of 1.65° and limited to only single-polarization. The newer antenna will have a beam width of 0.95° which will drastically improve the resolution and accommodate dual-polarization.

Table 2.5: The technical specifications of the NWU Lekwena radar

Radar parameter	**Before upgrade**	**After upgrade**
Magnetron frequency	5560 MHz	5620 MHz
Output Power (dB)	81.8 dBm	83.5 dBm
Output Power (W)	152.03 kW	222.56 kW
Duty Cycle	3.75 ms	3.75 ms
Pulse Width	3.75 us	2.0 us
Pulse Repetition Frequency	266.67	266.67
Minimum detectable signal	-108.8 dBm	-108.8 dBm
Maximum Range	200 km	200 km

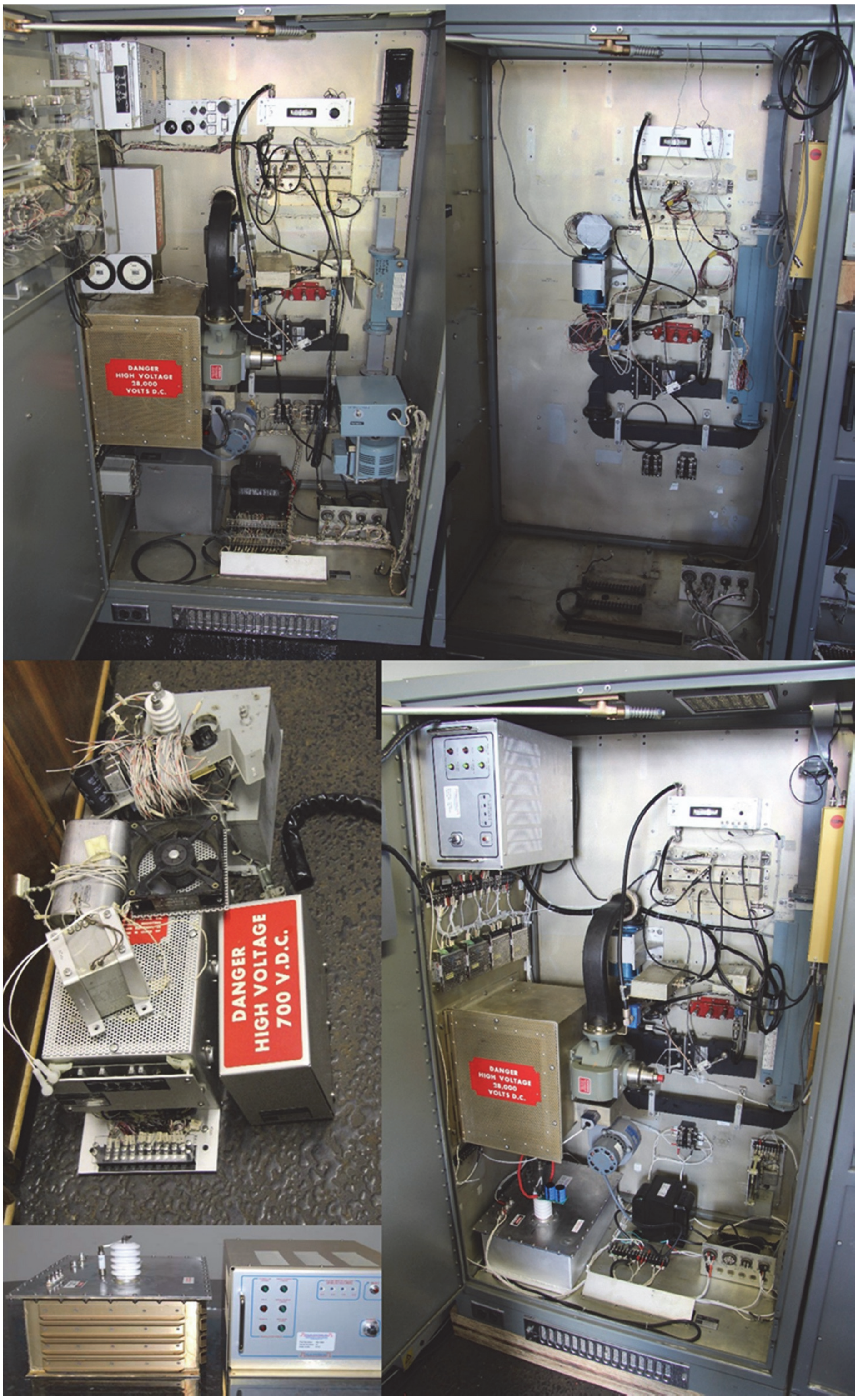


Figure 2.31: Photographs of the NWU Lekwena transmitter upgrade: the original EEC TR-1001 transmitter (top left); all the superfluous parts removed (top right); the removed parts (middle left); the new TR-1061 solid-state transmitter (bottom left); and the upgraded transmitter (bottom right)

2.3.12. Performance of the NWU Lekwena radar

The Lekwena radar is ideally situated between the Irene, Bethlehem and Ottosdal radars (Figure 2.32). The Mooi river network lies in the North Eastern quadrant between 15 km and 100 km from the radar (Figure 2.32). Intermittent interference from other sources, like wireless local networks, is detected by the radar (Figure 2.33). Although a nuisance, it provides an opportunity to find engineering solutions for this problem that has impeded the use of C-band radars in urban areas where radio interference is common.

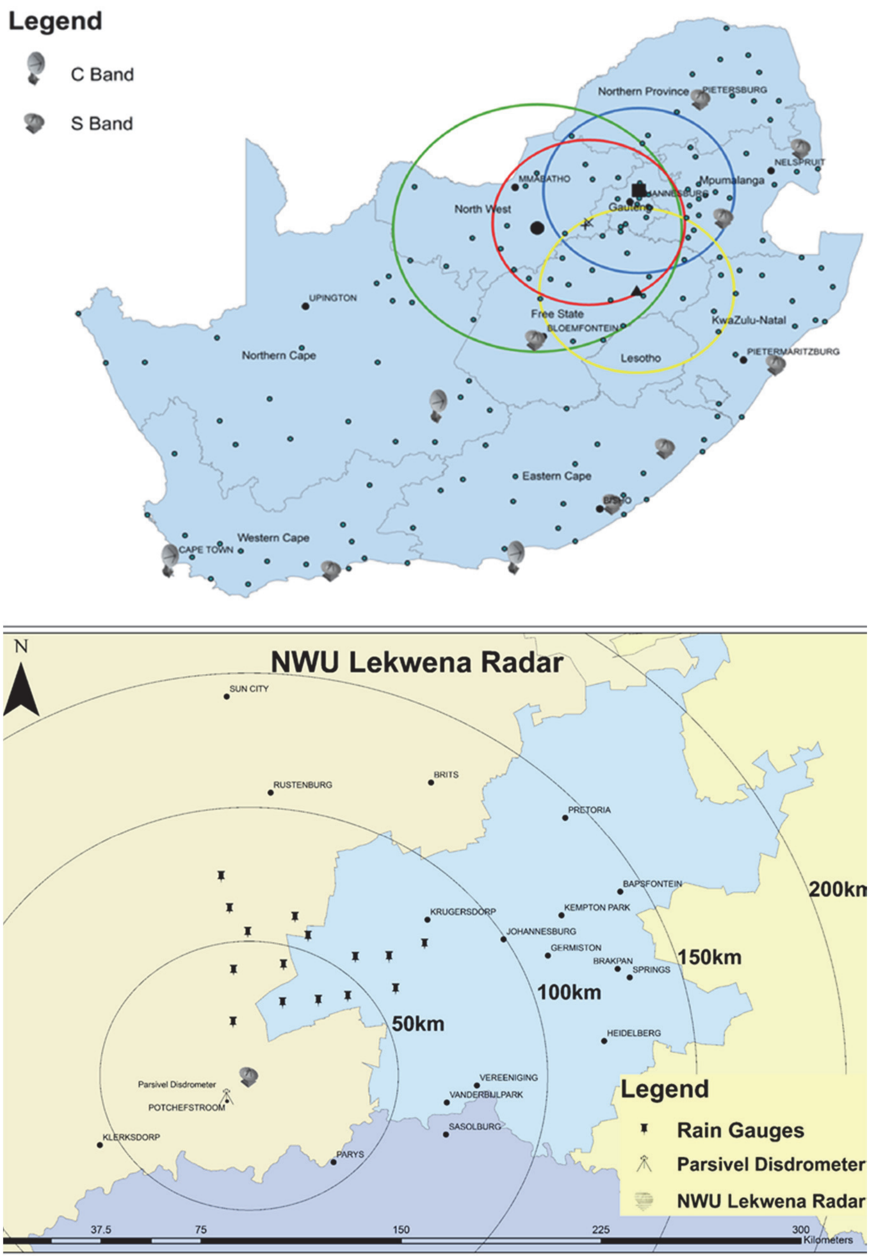


Figure 2.32: The coverage area of the Lekwena radar (top) and the positions of the Mooi River network relative to the radar.

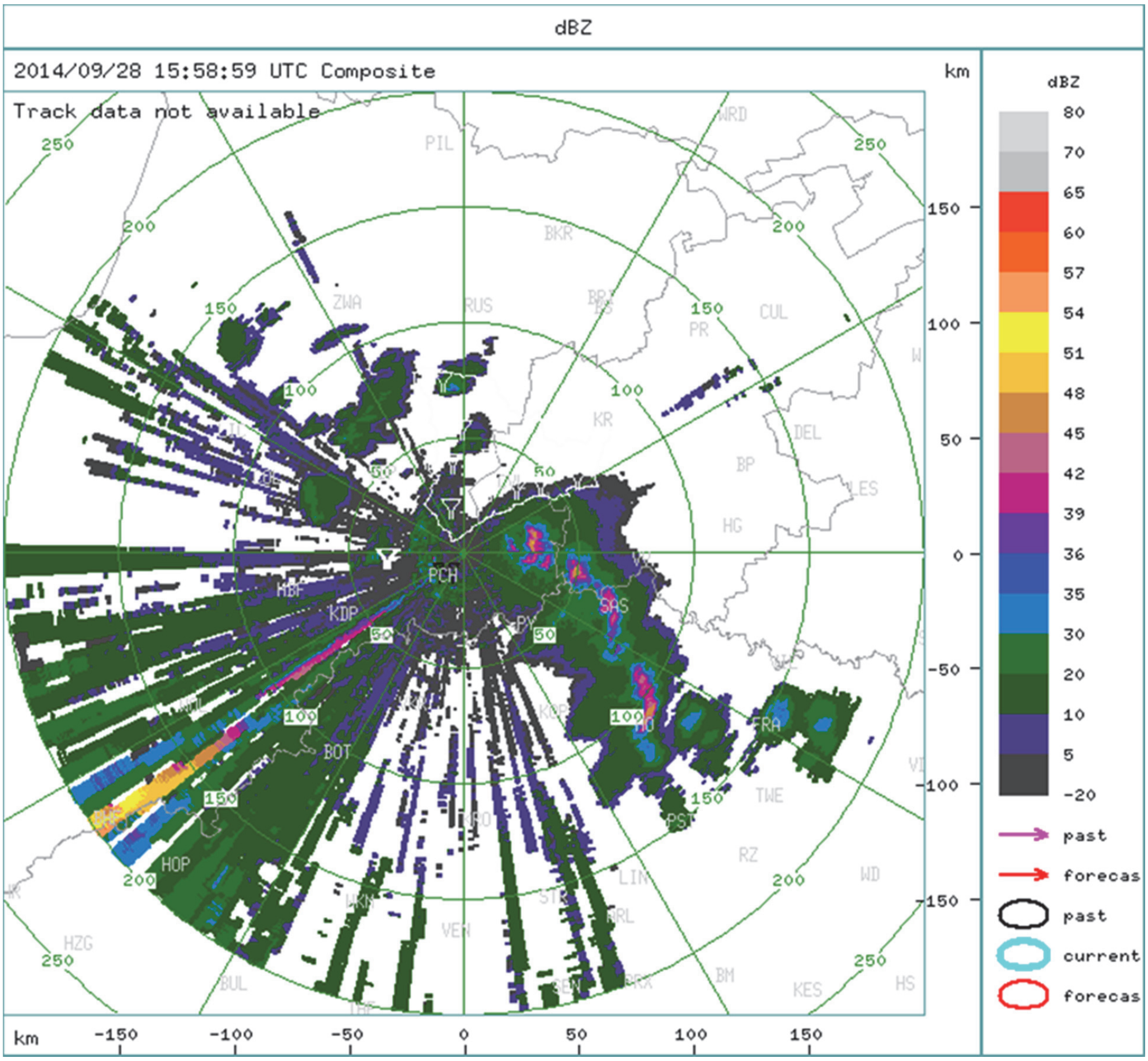


Figure 2.33: Interference from other transmitting sources observed by the NWU Lekwena radar.

Comparing the Lekwena radar with the Irene radar before and after (Figure 2.34) the transmitter upgrade reveals a 10dB low bias by the Lekwena radar. The range sensitivity of the Lekwena radar had a significant improvement after the upgrade, but the bias is still present. The likely cause is the signal generator used for calibration. This will be sent to the manufacturer for repair.

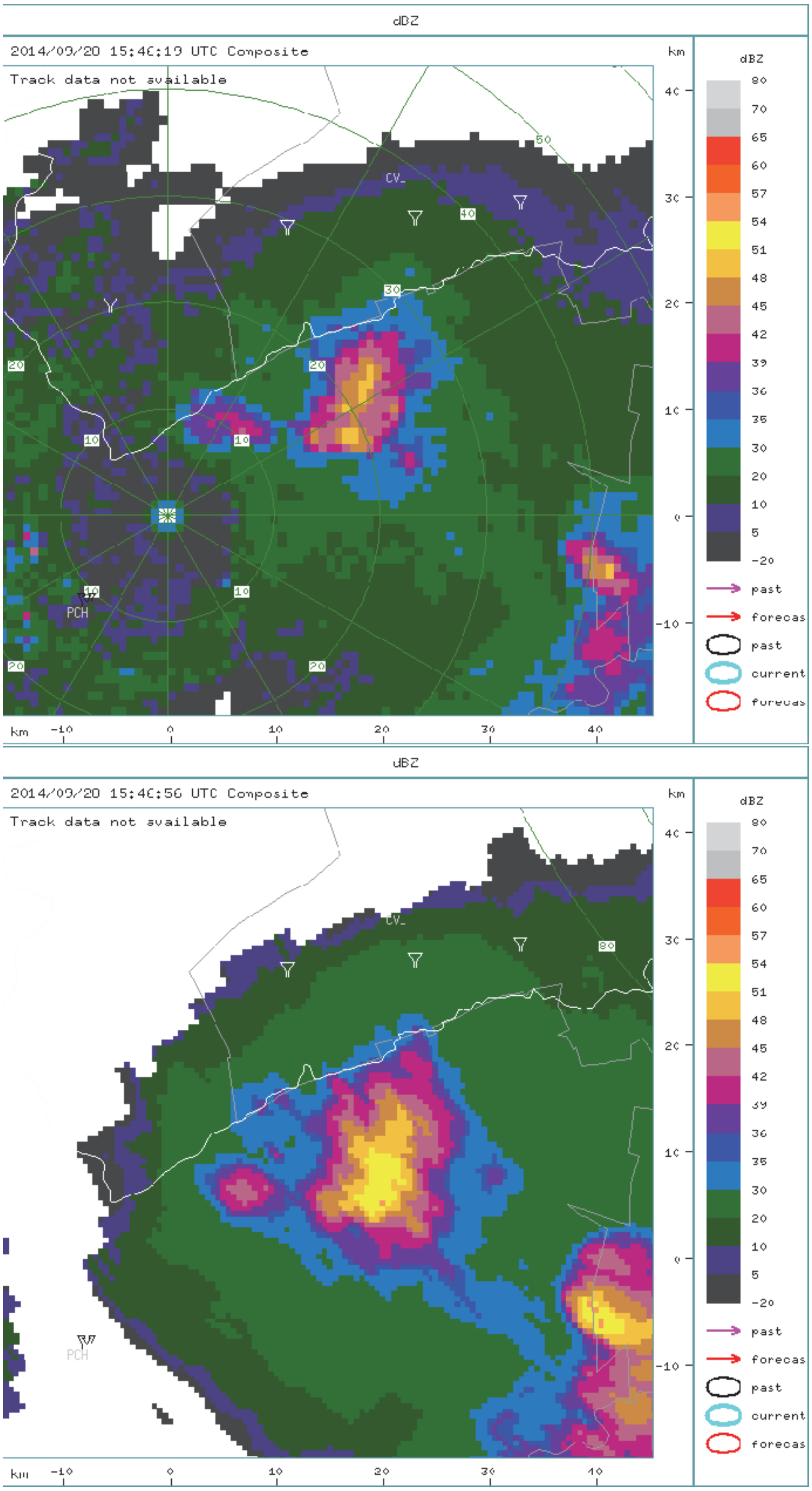


Figure 2.34: Comparison of the Lekwena (top) and Irene (bottom) radars before the transmitter upgrade

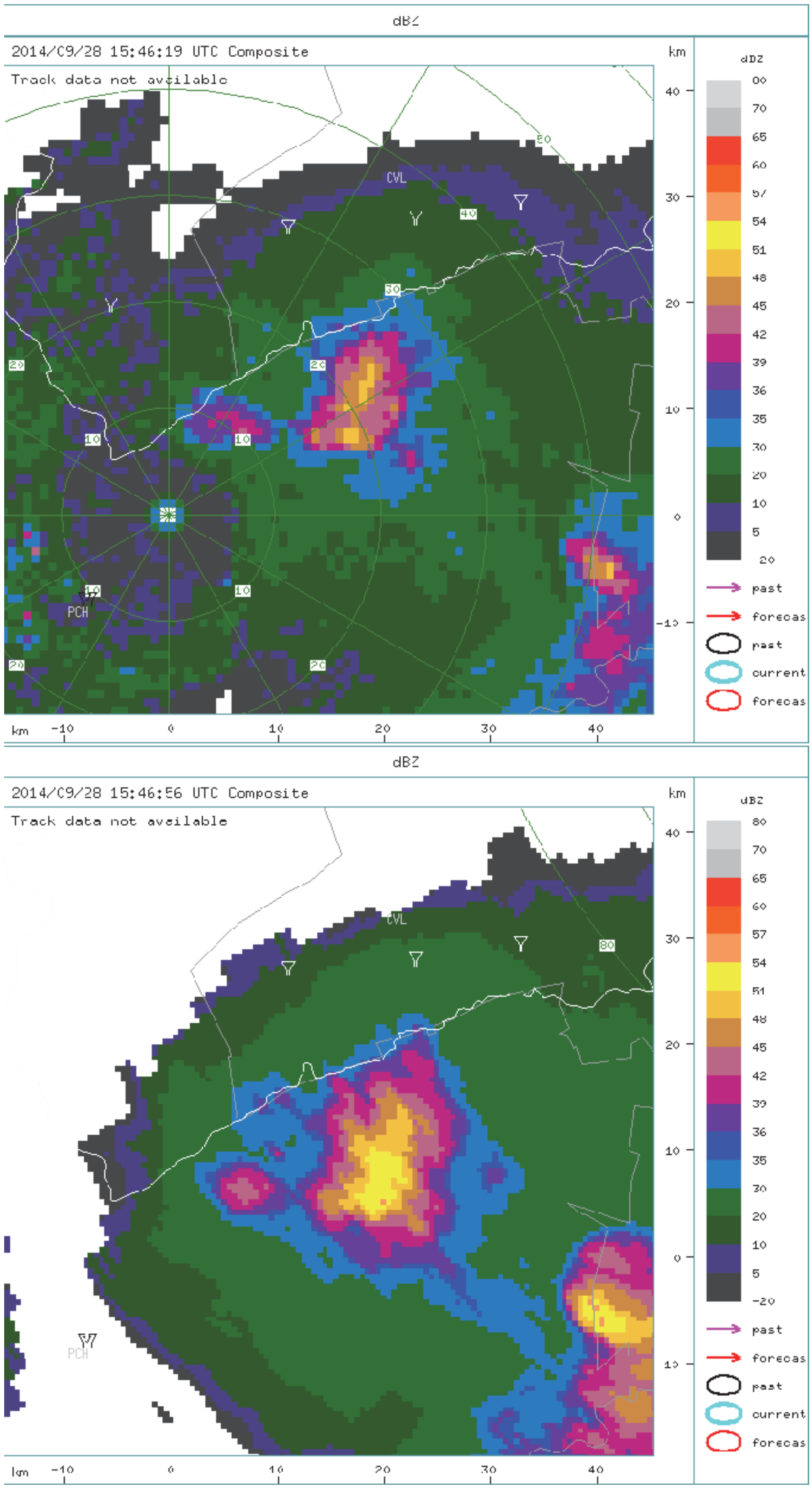
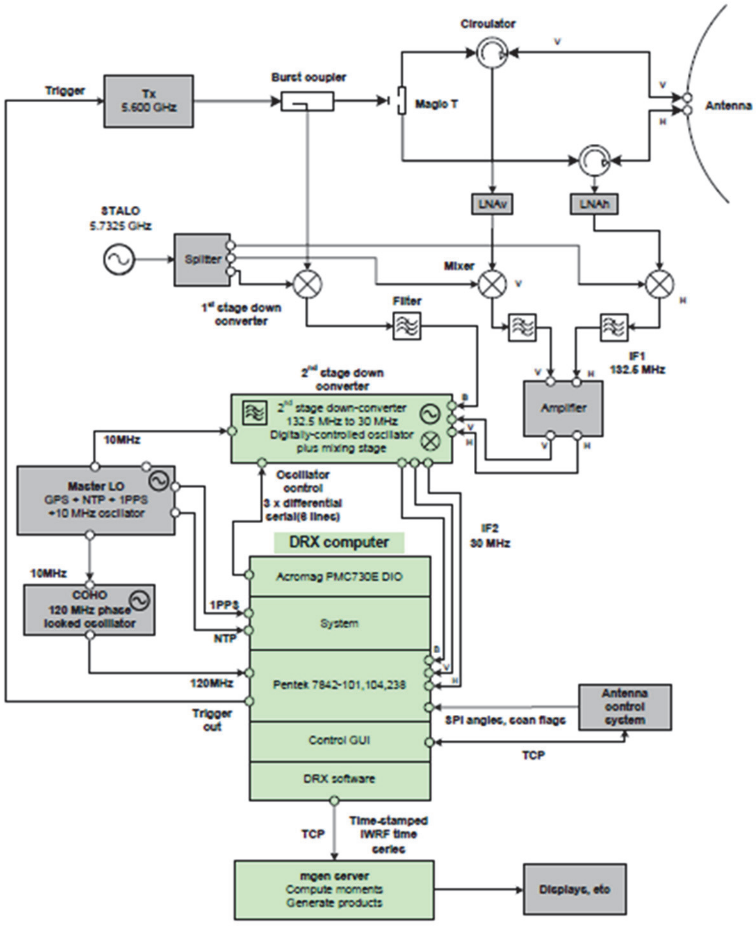


Figure 2.35: Comparison of the Lekwena (top) and Irene (bottom) radars before the transmitter upgrade.

2.3.13. Future plans for the NWU Lekwena radar

The next upgrade will be to replace the original receiver unit with a PENTEK DRX system designed by National Center for Atmospheric Research (NCAR). The major benefit of this upgrade it will enable the radar to measure dual-polarization, improving the minimum detectable signal, lower noise levels and better algorithms to predict storms. This upgrade is still in the planning phase. It will also be possible to retrieve dual polarized measurements if the necessary hardware modifications are made. A diagram of the current plan is shown in Figure 2.35.

Replacing the antenna with a larger one will also increase the resolution of the data. The current antenna is a 2.4 m diameter parabolic dish with a focus beam width of 1.65°. Over 200 km range the special resolution is 5.76 km, which is not ideal. The radar measures the entire beam width and generates an average for that specific scan. Over such a great distance most of the smaller storms will be shown as one big storm, lowering the resolution. To increase the overall resolution, the antenna will later on be replaced with a 3.6 m diameter parabolic dish which will improve the beam width to 1°.



Schematic for dual-polarization magnetron-based system

Figure 2.36: A diagram of the proposed receiver upgrade

3. Characterizing Rainfall in The Mooi River Network

3.1. Climate of the Mooi river network

The different rainfall regions as obtained from correlating all available data from the SAWS database is shown in Figure 3.1. The climate for the Mooi River Network is moderate with predominantly summer rainfall occurrence as shown in Figure 3.4 and in the climate statistics of the SAWS weather stations in Carletonville (Table 3.1), Potchefstroom (Table 3.2), Rustenburg (Table 3.3) and Krugersdorp (Table 3.4). All three regions receive the most of their annual rainfall between November and March, with January being the month where the most rain is recorded across all three regions and July receiving the least rain each year (Figure 3.4). SAWS have kept records of the South African climate since the early 1900s. The weather service maintains a climatological data set which has classified all the SAWS weather stations into regions of similar rainfall. The Mooi River Network falls within three of these climate regions (Region no: 84, 85 and 74) as shown in Figure 3.1. These regions were delineated using the Thiessens polygons interpolation technique. There are some artifacts on the boundaries of the regions that look unrealistic (Figure 3.1). This is because topography has not been included in the delineation of the regions.

The general shift in the east-west gradient of rainfall distribution for South Africa is reflected in the annual rainfall data of climate stations located in the Mooi river network. As shown in Figure 3.4, there is prominent negative east-west gradient in annual rainfall over the Mooi river network, where region 74 has the highest median annual rainfall and region 84 has the lowest median annual rainfall. The maximum annual rainfall for region 74 which is the eastern part of the Mooi river network is 950 mm and the minimum is 420 mm. The interquartile range of annual rainfall for region 74, varies between 780 and 610 mm. Region 85 which is located in the north and western parts of the network, between region 74 and 84 and has a maximum annual rainfall 910 mm and a minimum of 380 mm. The interquartile range of annual rainfall for region 85, varies between 710 and 560 mm. Region 84 which is the southern part of the network has a maximum annual rainfall of 905 mm and a minimum of 370, which is very similar to region 84. However, the inter-quartile range of region 84, which varies between 680 and 480 mm, is slightly more than the inter-quartile range of region 85. This indicates that although these two regions are next to each other, region 84 has more variable annual rainfall than region 85 between 1920 and 2014.

Figure 3.4 gives the cumulative frequency distribution of the total daily rainfall for all SAWS stations that fall within the three climate regions within the Mooi river network. The east-west gradient that is observed in Figure 3.4 can again be observed here. It is also evident that for 50% of rainfall events in these three regions rainfall of less 7 mm are recorded, 70% of events record less than 12 mm of rain and 90% of events record rainfall of less than 23 mm. Thus it can be said that it is highly unlikely for rainfall of more than 10-20 mm to be recorded during most events over the three climate regions.

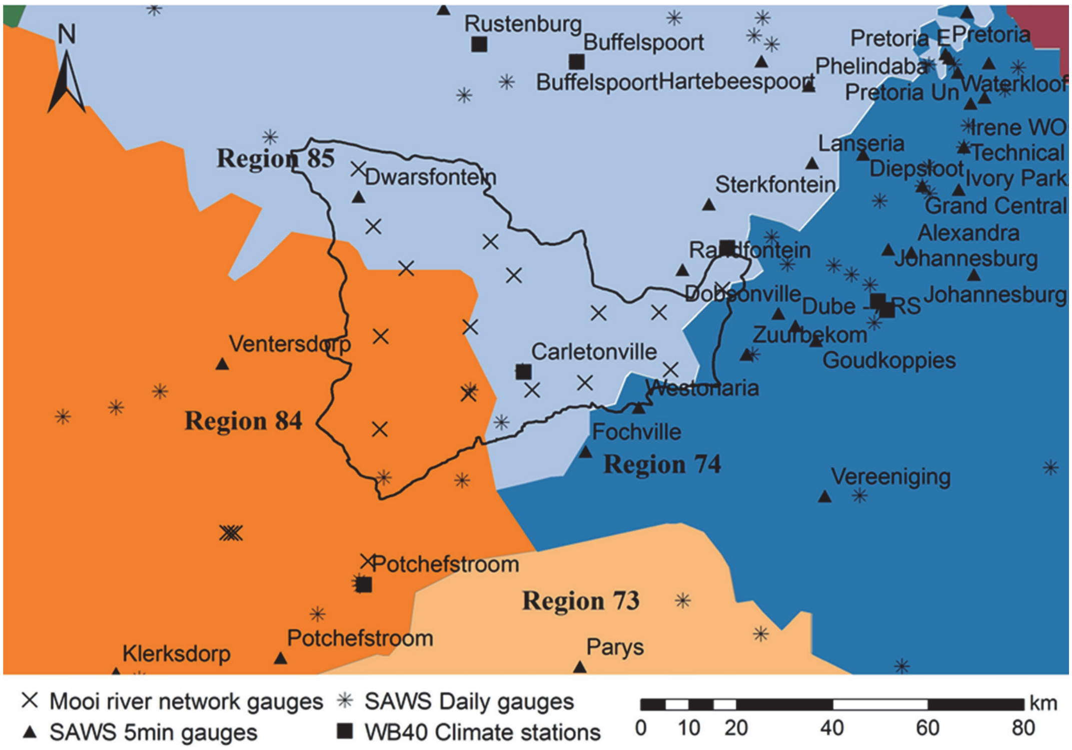


Figure 3.1: A map of the different climate regions for the Mooi River Network area as classified by SAWS

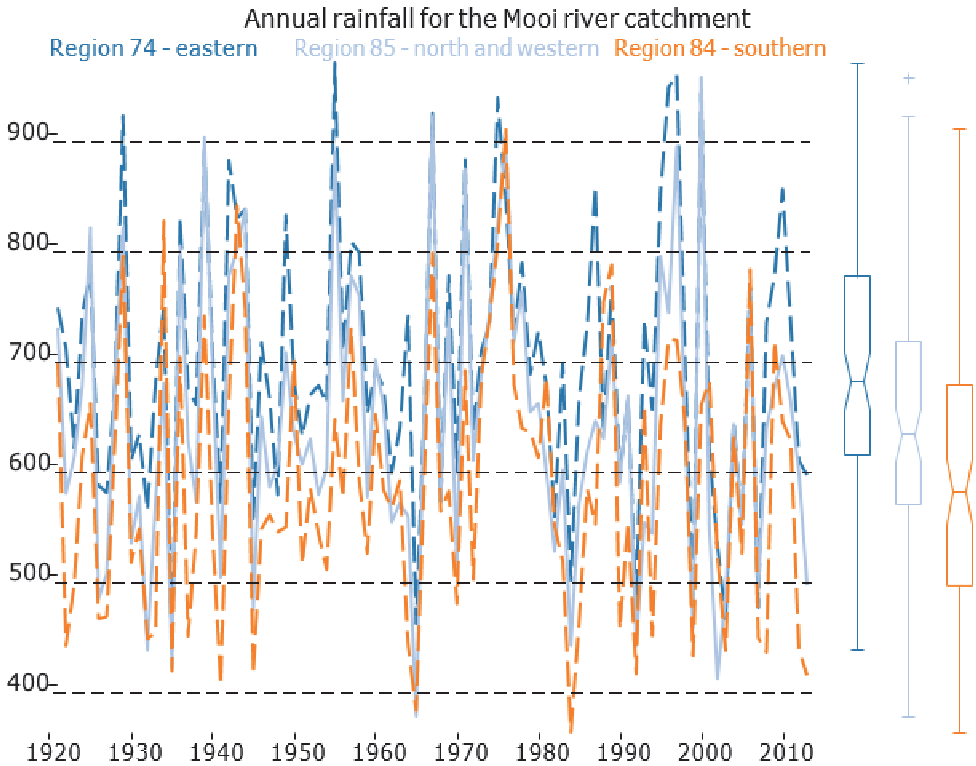


Figure 3.2: Annual rainfall for the southern (region 84), north and north-western (region 85) and eastern (region 74) parts of the Mooi river network between 1920 and 2014.

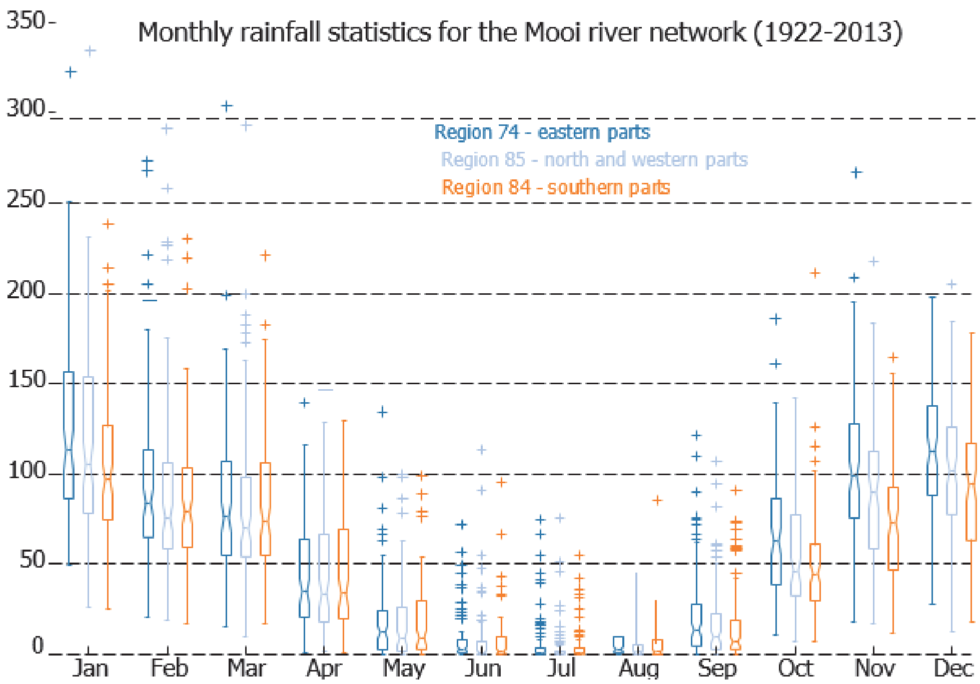


Figure 3.3: Monthly rainfall statistics for the southern (region 84), north and north-western (region 85) and eastern (region 74) parts of the Mooi river network between 1920 and 2014

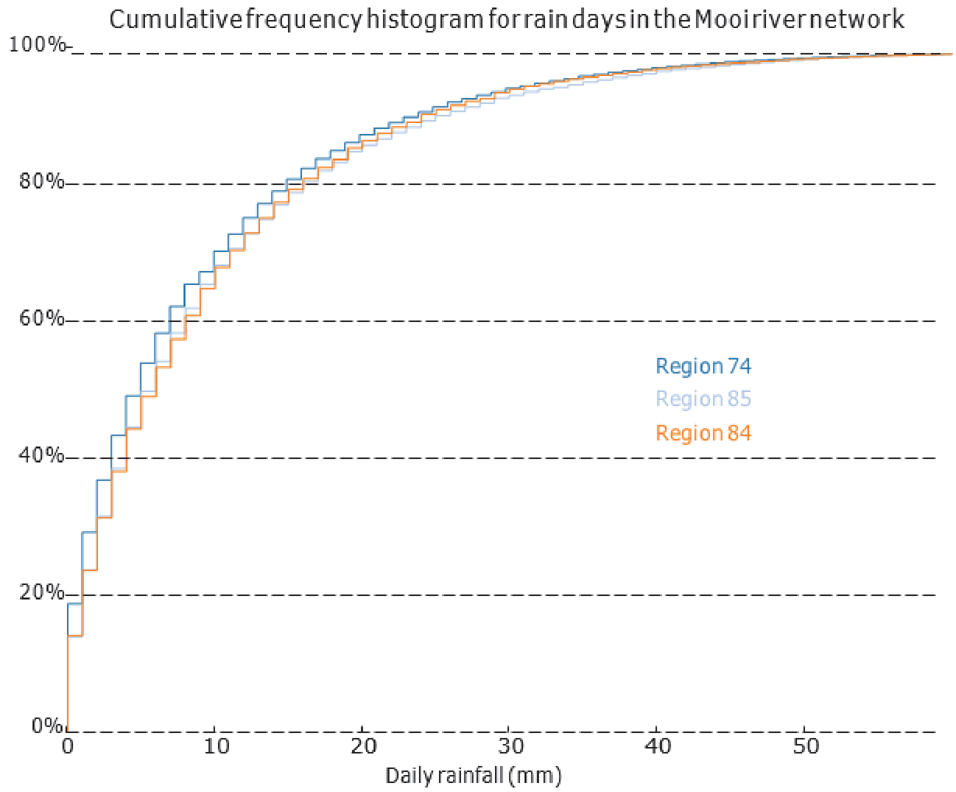


Figure 3.4: Cumulative frequency distribution of daily total rainfall for all SAWS stations in the southern (region 84), north and north-western (region 85) and eastern (region 74) parts of the Mooi river network between 1961 and 2014

Table 3.1: Rainfall climate statistics for the SAWS station at Carletonville (PUR), located at -26.333333, 27.383333 for the period 1955-1984

No of days with		Precipitation (mm)						Frequencies							
								Precipitation							
		Max in 24h		Highest Monthly Max & Date		Lowest Monthly Max & Date		≥0.1mm			≥1.0mm			≥ 10mm	Hail
Month	Average							Ave	Max	Min	Ave	Max	Min	Ave	Ave
	Σ	mm	Date	Σ	Date	Σ	Date								
P	30	30		30		30		30.0	24	24	30.0	30	30	30	16
1	122	71	1978/21	272	1974	32	1956	13.5	23	6	10.8	20	5	4.2	0.2
2	86	111	1962/15	204	1966	29	1970	9.3	18	4	7.5	14	4	2.8	0.1
3	77	79	1976/19	204	1976	3	1966	9.1	13	4	7.5	14	2	2.7	0.2
4	60	72	1971/07	201	1971	5	1956	6.6	11	1	5.9	12	1	2.0	0.4
5	18	33	1976/03	75	1969	0	1982	3.3	10	0	2.6	8	0	0.7	0.4
6	7	27	1957/11	51	1957	0	1982	2.0	7	0	1.5	7	0	0.4	0.0
7	6	34	1957/02	68	1957	0	1981	1.8	7	0	1.3	7	0	0.4	0.0
8	7	33	1979/20	81	1979	0	1982	2.0	9	0	1.3	6	0	0.2	0.1
9	19	30	1977/22	96	1957	0	1975	3.9	13	1	2.4	9	0	0.5	0.8
10	64	102	1969/18	169	1969	8	1968	7.9	14	3	6.3	13	1	2.1	0.3
11	96	73	1976/21	216	1963	24	1982	10.6	17	3	8.8	15	2	3.0	0.9
12	108	159	1976/08	252	1976	40	1962	12.2	18	6	9.8	15	5	3.6	0.4
A	670	159	1976	1112	1976	421	1965	82.2			65.7			22.6	3.8

Table 3.2: Rainfall climate statistics for the SAWS station at Potchefstroom (AGR), located at 26.733333, 27.083333 for the period 1903-1984

Month	Average	Max in 24h		Highest Monthly Max & Date		Lowest Monthly Max & Date		≥0.1mm Ave	≥0.1mm Max	≥0.1mm Min	≥1.0mm Ave	≥1.0mm Max	≥1.0mm Min	≥10mm Ave	Ave Hail
	Σ	mm	Date	Σ	Date	Σ	Date								
P	80	51		80		80		80	33	33	80	53	53	80	26
1	111	95	1977/31	258	1976	29	1933	13.2	19	6	9.9	17	4	3.6	0.4
2	95	79	1983/28	227	1907	8	1984	10.1	16	4	8.1	13	2	3.1	0.2
3	81	78	1975/18	276	1921	8	1983	10.2	17	4	8	15	3	2.7	0.3
4	46	83	1965/13	160	1971	0	1944	7.7	17	2	5	12	0	1.8	0.3
5	19	44	1950/03	99	1936	0	1982	3.8	10	1	2.5	8	0	0.7	0.2
6	8	61	1944/13	104	1944	0	1982	1.5	6	0	1	5	0	0.2	0.1
7	8	41	1957/02	83	1918	0	1981	1.5	9	0	1	8	0	0.2	0
8	9	39	1979/20	100	1922	0	1982	1.5	7	0	1	6	0	0.2	0
9	18	53	1940/25	93	1940	0	1983	3.5	12	0	2	11	0	0.6	0.3
10	50	72	1951/20	171	1913	1	1919	7.8	16	3	5.4	12	1	1.5	0.7
11	79	83	1939/03	170	1936	10	1941	12	21	3	8.3	18	1	2.7	0.5
12	101	140	1943/12	237	1909	21	1948	12.7	19	7	8.9	16	2	3.7	0.3
A	625	140	1943	980	1976	365	1903	85.5			61.1			21	3.3

Table 3.3: Rainfall climate statistics for the SAWS station at Rustenburg (AGR), located at -25.71667,27.3 for the period 1951-1984

Month	Average	Max in 24h		Highest Monthly Max & Date		Lowest Monthly Max & Date		≥0.1mm Ave	≥0.1mm Max	≥0.1mm Min	≥1.0mm Ave	≥1.0mm Max	≥1.0mm Min	≥10mm Ave	Ave Hail
	Σ	mm	Date	Σ	Date	Σ	Date								
P	34	34		34		34		34	34	34	34	34	34	34	28
1	138	82	1978/02	344	1978	35	1984	13.6	19	7	10.8	16	6	4.0	0.3
2	98	77	1973/25	212	1956	20	1982	10.7	17	4	8.3	14	3	3.2	0.2
3	76	138	1976/19	252	1976	10	1965	10.1	16	3	7.5	15	2	2.3	0.1
4	57	82	1961/01	181	1971	0	1956	7.1	14	1	5.6	13	0	1.7	0.1
5	17	45	1951/15	87	1956	0	1978	2.9	8	0	2.2	8	0	0.4	0.0
6	8	82	1957/10	133	1957	0	1982	1.6	6	0	1.1	5	0	0.3	0.0
7	5	40	1957/02	79	1957	0	1981	1.2	6	0	1.0	5	0	0.1	0.1
8	7	36	1957/24	41	1979	0	1982	1.9	7	0	1.3	7	0	0.2	0.1
9	17	47	1977/27	92	1957	0	1968	3.1	11	0	2.0	8	0	0.5	0.3
10	53	65	1976/02	124	1956	6	1965	8.0	18	2	5.7	14	1	1.8	0.4
11	98	104	1979/25	205	1979	12	1951	11.6	19	5	9.1	16	2	3.1	0.6
12	111	96	1954/06	272	1966	25	1984	13.2	19	7	10.1	16	3	3.4	0.0
A	685	138	1976	1067	1962	370	1965	85.0			64.7			21.0	3.0

Table 3.4: Rainfall climate statistics for the SAWS station at Krugersdorp (MUN), located at -26.1,27.7667 for the period 1951-1984

	Precipitation (mm)							Frequencies							
No of days with								Precipitation							
Month	Average	Max in 24h		Highest Monthly Max & Date		Lowest Monthly Max & Date		≥0.1mm			≥1.0mm			≥ 10mm	
								Ave	Max	Min	Ave	Max	Min	Ave	Ave Hail
	Σ	mm	Date	Σ	Date	Σ	Date								
P	34	34		34		34		34.0	34	34	34.0	34	34	34	20
1	146	116	1978/27	440	1978	56	1969	15.2	22	8	11.4	20	3	4.2	0.8
2	109	80	1959/03	321	1955	24	1982	12.0	19	5	9.7	15	3	3.7	0.3
3	92	104	1976/19	227	1977	13	1966	12.0	19	3	9.4	15	2	2.7	0.1
4	64	61	1960/23	145	1971	0	1956	8.4	17	0	6.7	16	0	2.0	0.3
5	23	112	1976/03	124	1976	0	1982	3.9	10	1	2.9	7	0	0.5	0.2
6	8	34	1957/11	71	1957	0	1982	2.1	10	0	1.5	7	0	0.2	0.0
7	9	37	1957/01	94	1957	0	1981	1.5	7	0	1.1	7	0	0.2	0.1
8	7	28	1957/24	57	1979	0	1982	2.2	10	0	1.5	7	0	0.1	0.0
9	23	38	1981/10	97	1957	0	1975	3.9	12	0	2.6	10	0	0.7	0.3
10	68	49	1976/02	163	1969	15	1965	9.7	18	4	7.4	14	3	2.3	0.4
11	109	61	1955/21	199	1962	27	1982	13.7	20	7	10.7	16	5	3.9	0.9
12	109	57	1983/30	210	1983	29	1962	14.5	20	9	11.2	17	5	3.7	0.5
A	767	116	1978	1227	1955	427	1965	99.1			76.1			24.2	3.9

3.2. Rain rates in the Mooi river network

Rainfall is a dynamic process that varies in space and time. Convective storms are usually localized events that tend to be of short duration and high intensity, whereas stratiform events are wide spread and can last for long periods of time. The rainfall that occurs in the Mooi river network is no exception to this. As indicated by Figure 3.5, there is considerable spatial as well as temporal variation of rainfall measured between the rain gauges of the Mooi river network. The spatial correlation between the rain gauges of the Mooi river network improves as the accumulation time increases. The correlations of one-minute rainfall over the network is the lowest, where a correlation of 0.2 for the two closest rain gauges (10 km apart) is found and from there on the correlations of one-minute rainfall only decreases, with almost no correlation for gauges that are separated by more than 30 km. On the other hand, at the longer timescales such as daily rainfall and longer, there is a significant increase in the correlation. The gauges that are 10 km apart have a very good correlation of 0.8 and between the two gauges that are furthest apart (75 km), the correlation decreases to 0.2. It is evident that the Mooi river network is dense enough in space to provide rainfall data for water management and agricultural practices, which require rainfall data of longer time scales, but for applications such as radar calibrations and flash flood modelling/mitigation that require extremely fine temporal resolution of one minute to five-minute averaging periods, the network is not dense enough because of the poor spatial correlations of the minute to 30-minute averaging periods.

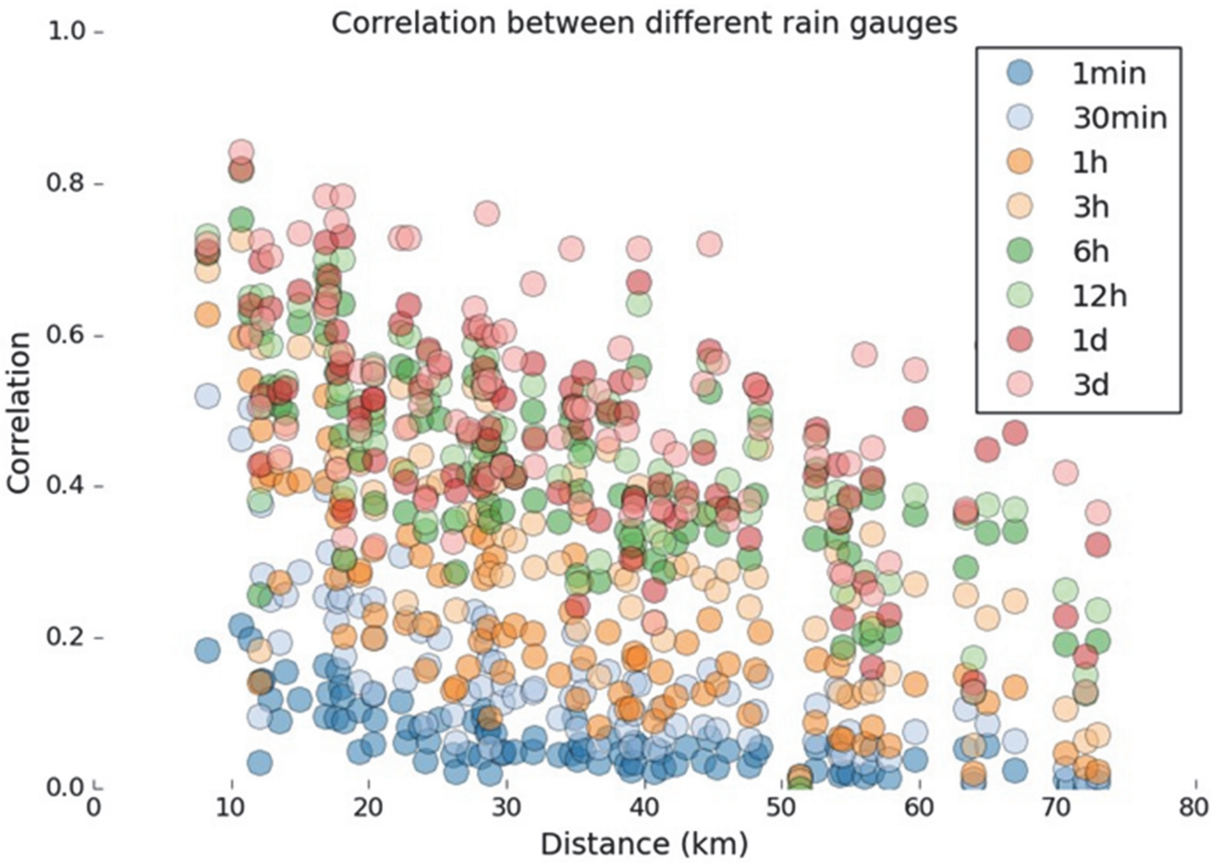


Figure 3.5: The spatial correlation between rain gauges in the Mooi river network as a function between space and time

4. Improving Single-Parameter Radar Estimates of Rainfall

The need for improved radar rainfall estimates has never been greater in Africa. The effects of climate change are becoming more evident. These affects are especially being felt in developing countries. This is a cause for concern as climate change has a direct impact on human and environmental health. Since 1950 there have been a number of changes observed in extreme weather and climate events (IPCC, 2014).

Operating a weather radar in a developing country poses unique challenges. Africa is prone to severe weather conditions ranging from hail storms to cyclones, all with devastating effects on a country's economy and infrastructure. Remote sensing instruments, like radar, provides the opportunity to observe large areas with a minimal infrastructure footprint. Understanding these storms will improve our readiness, forecasting and prediction of these storms. The South African Weather Service has an extensive weather radar network across South Africa. In the following chapter an overview of the current infrastructure for precipitation estimation in South Africa is discussed and potential methods of improving these estimates is proposed. The challenges and operational constraints are reviewed. In this context, optimized algorithms for precipitation estimation in this setting are shown. Re-engineering and redeploying old radars is a cost-effective means of extending the coverage area of a national weather radar network. Even new generation radars are typically single polarized radars being operated for maximum coverage area.

With budget constraints being a big issue in South Africa development and capacity building in new rainfall measuring techniques has not developed. Developing countries has also fallen behind in terms of new technologies and ways to measure radar rainfall estimates and new radar operation techniques as South Africa is still stuck with single polarized radars whereas weather radars in developed countries has dual polarized capabilities. Therefore, new and unique observation techniques with the current resource that we have are needed to keep up with the developed countries. Using new innovative ways to improve this data such as stratifying events in to convective and stratiform and deriving new Z-R relations for each event is important.

4.1. Reflectivity vs rain rate relationships

Radars use reflectivity to measure rainfall. The reflectivity (Z) which is measured in dBz is then converted to rain rate (R) on the ground. The Parsivel disdrometer measures both of these variables simultaneously which makes the disdrometer a very handy instrument for the validation of radar data due to its ability to extend measurements of reflectivity to the ground. The direct measurement of the Z-R relation in a specific event for a specific climate can increase the accuracy of radar rainfall estimates by applying the derived Z-R relation. The Z-R relation includes:

$$Z = AR^b \tag{4.1}$$

where the Z is reflectivity and the R is the rain rate (Ulbrich and Miller, 2000; Kajewski and Smith, 2002). A and B are coefficients that may vary from one location to another and between seasons. These coefficients are independent of R and Z itself (Uijlenhoet, 2001). Large scale variation and dramatic changes occur in the Z-R relation within individual storms and between storms (Atlas et al., 1999). Most radars around the world, including those operated by SAWS, is set to the default Z-R relation namely the Marshall and Palmer (Marshall and Palmer, 1948). This is a Z-R relation that has been calculated by Marshall and Palmer and it is mutually agreed around the world that it is the most accurate for the widest range of climates and events. The Marshall and Palmer relation is derived from 69 different relations (Marshall et al., 1955):

$$Z = 200R^{1.6} \tag{4.2}$$

Deriving a new Z-R relation measured for a specific climate and events can improve the reliability of radar data. It is also important to note that this is not the only factor that needs to be taken in account to better the radar measurements. Calibration offsets between radar and Parsivel data and bias measurements must also be taken into consideration to better the reliability and accuracy of data (Ulbrich and Miller, 2000). Calculating a new Z-R relation involves measurement made by the disdrometer on the ground. This is then implemented in the conversion of the radar data and compared to estimates estimated by the Marshall and Palmer. The disdrometer was placed at the North West University in Potchefstroom, North West. The radar that was used was the Irene weather radar situated in Pretoria, Gauteng. The disdrometer was placed in close proximity to tipping bucket rain gauge for comparison and calibration purposes. Comparing the rainfall accumulation by both the disdrometer and the rain gauge was done to establish whether there is any calibration or operating problem with any of the two instruments. Never before in South Africa have measurements been made by using a Parsivel disdrometer.

The Parsivel disdrometer was deployed between the 21st of February and the 31st of March 2014. During this time 60 events were measured and a 180 mm of rain was observed. These 60 events were analysed to determine whether the events are significant or not. Significance was determined by 3 variables. Firstly, the maximum rain rate and reflectivity of each storm was determined. This was a good indicator to identify convective storms on the Highveld. However, this is not a good indicator for stratiform rain and therefore the amount of data measurements was used to include stratiform rain, which is small in rain rates but long in duration (Table 4.1).

Table 4.1 shows that convective and stratiform events were measured. Normally events with a high maximum rain rate (Rain Max) and reflectivity (dBz Max) would have a low number of data measurements due to its high intensity but short duration. Stratiform events are categorized by its low rain rate and reflectivity measurements but high number of data points. In Table 4.1 can be seen that both these types of events have been included. Out of a possible 60 vents which was identified by a 30-minute gap between measurements 18 events was chosen.

Table 4.1: Various Rainfall Measurements

Start	End	Max Parsivel Rain Rate (mm/h)	Mean Parsivel Rain Rate (mm/h)	Max Gauge Rain Rate (mm/h)	Mean Gauge Rain Rate (mm/h)	Max Parsivel Reflectivity (dBz)	Mean Parsivel Reflectivity (dBz)	Max radar Reflectivity (dBz)	Mean Radar Reflectivity (dBz)	A	R	B	Duration (minutes)
2014/2/23 13:40	16:30	4.2	1.2	5.4	1.4	33.4	21.0	40.5	28.0	1.6	242.1	1.00	160
2014/3/05 07:50	11:10	27.5	3.67	28.1	4.0	42.6	22.2	38.5	21.8	1.4	149.1	0.97	190
2014/3/08 10:55	11:45	21.1	3.5	9.5	2.5	46.8	23.6	36.2	24.1	1.5	282.1	1.09	40
2014/3/09 15:45	17:15	62.3	9.5	61.6	9.3	50.7	21.9	59.6	32.0	1.5	208.3	0.98	80
2014/3/18 13:45	14:35	21.4	7.3	24.1	7.9	43.7	25.6	41.5	28.4	1.6	168.6	0.98	40

These events were mostly formed because of the easterly movement of air. Warm moist air is transported by these easterly wave systems to the country. The development of a low pressure system normally occurs with this which creates ideal condition for cloud development and rain. Other synoptical conditions that also brings rain to the Highveld occurs when the South Indian High pressure system moves close to the country. This system is situated just east of the coast of South Africa. With very warm sea temperature the air is very moist, as this air is brought inland it raises orographically, condensates and rains. The ridging high pressure system can also bring rain but normally does not influence the Highveld region.

As already mentioned the South African Weather Service has an extensive cutting edge weather radar network across South Africa. These radars have been bought for millions of dollars and therefore using them to their optimum potential is of utmost importance.

Climatologists use the Z-R relation to extend the reflectivity measurement measured aloft to the ground. By using the theoretical Z-R relation accuracy issues may arise as this is a generic equation is not developed for the specific climate and storms of the Highveld. By using a Parsivel disdrometer and measuring rain rate and reflectivity simultaneously on the ground a new unique Z-R relation for each storm has been calculated. Table 4.1 shows the A and b coefficients measured for each event which can be implemented in equation 4.2. It also shows the correlation between the rain rate and the reflectivity measurement.

Convective events normally have low A values whereas stratiform events have higher A values. Figure 4.1 presents the different A and b values and categorize the events by the maximum rainfall intensity.

Figure 4.1 shows that a cluster of convective events do occur in the middle of all the Z-R relations. These events are identified by high intensity represented by the bigger circles in fig 4.1. Convective events normally have lower A values than stratiform rain.

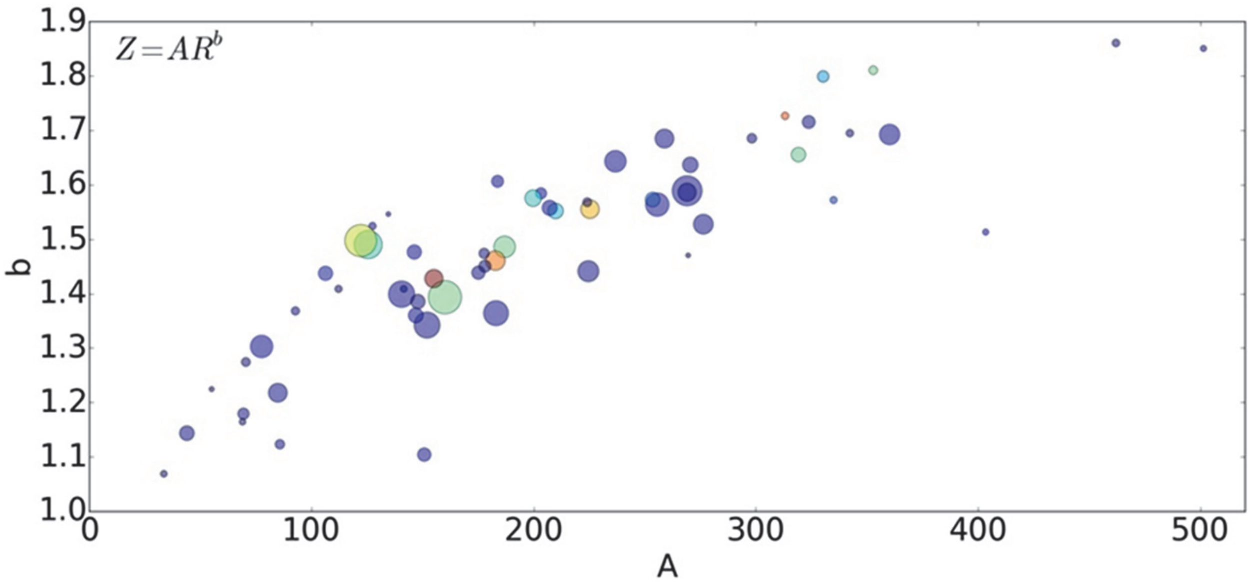


Figure 4.1: Z-R relation of different events categorized by the maximum rainfall intensity

Case studies were used to implement these changes. Five case studies was used which included three convective events and two stratiform events. These events were identified according to the maximum rain rate and reflectivity measured by the Parsivel for convective events and for stratiform events the duration of rainfall was used. A new unique Z-R relation was measured for each of the storm and the accumulation of rainfall was compared to the theoretical Marshall and Palmer relation.

The first case study (Figure 4.1) was measured on 23 February 2014. A total of 3.3 mm of rain was observed and the duration was 160 min. An event that long in duration with that small amount of rain is normally a stratiform event. As already mentioned stratiform events has got a much higher b coefficient than convective event. With a b coefficient of 242 (Table 4.1) this storm event matches the description of a stratiform event. According to the synoptical chart this widespread rainfall with some isolated convective events was formed from warm moist air from the equator brought inland. The easterly low over the country causes this moist air to rise which is ideal conditions for rainfall.

There is not a significant change in the Z-R relation. This can be that the Marshall and Palmer Z-R relation is more suited for stratiform events and therefore the new Z-R relation does not make a significant change. Even though this event is identified as a stratiform event there is some isolated convective events which also can cause problems. The Max DBZ shows that there was significant convective activity during the entire day.

The next event that was used as a case study was measured on 5 March 2014. A similar event on 23 January had a very long duration with low rain rate and reflectivity values (Figure 4.5). The rain gauge measured 11.3 mm of rain for that day and the duration of the event was 190 min. With the easterly movement of air from the equator the condition is ideal for widespread rainfall.

The implementation of the new derived Z-R relation makes a significant change to the radar rainfall estimates. The Max DBZ shows that the convective events that was around on this day was not that significant. Therefore, the closer correlation between the ground truth value measured by the rain gauge and the radar rainfall estimate using the new Z-R relation. The Marshall and Palmer relation underestimates the event and the new Z-R relation increases the values.

The next event was measured on the 8th of March 2014. With a duration of 40 minutes and a maximum rain rate of 21 mm/h is this event classified as a convective event. These events are normally very high in rain rates and reflectivity, very localized and have a short duration. A total of 2,3 mm was measured due to its short duration. The synoptic chart shows two dominant systems that are both known to bring rainfall to the country. Firstly, the easterly wave is prevalent across the Northern side of the country bringing in moist air and raises due to the low pressure system. Secondly, a ridging high as developed south of the country bring warm moist air due to the movement over the warm Indian Ocean. This air raises orographically which causes clouds and rain.

It can be seen in the Max DBZ figure that convective storms do occur much more isolated than stratiform event. The Marshall and Palmer has also overestimated the rainfall accumulation and therefore the new Z-R relation lowers the accumulation.

The next case study was measured the following day on 9 March 2015. This was a very big convective storm with extremely high dBz values and a maximum rain rate of 62 mm/h. The duration of this storm was 80 minutes and a total of 12 mm of rain was measured. The synoptical chart showed that the easterly wave was once again present which does occur for most rainfall days in the summer. The ridging high pressure system was also visible with a long path over the warm Indian ocean. This brought very intense convective events to the Highveld. The maximum dBz that was measured by the radar was 60dbz which is more than the hail threshold of 55 dBz. The Highveld received a number of hail producing systems on this day. All observations show that this is a typical summer high intensity rainfall event.

These events were very localized. The gray area on the Max DBZ figure is areas of high reflectivity values and normally hail. The new Z-R relation had a slight increase in rainfall accumulation. The reason why there was only a slight increase in rainfall accumulation is because the Z-R relations was very similar. With a b coefficient of 200 and 208 the Marshall and Palmer and the New Z-R relation showed good correlation.

All of the data that was measured by the Parsivel and Z-R relations was generally derived for mixed event, convective events and for stratiform events. Mixed event included all of the data from 21 of February to 31 March 2014. This included both stratiform and convective events.

Events were stratified by using stratiform filter, an application of TITAN. Firstly, convective events were identified and the reflectivity and rain rate measurements made by the Parsivel was compared to each other.

The new Z-R relation (Figure 4.7) measured by the Parsivel showed a good correlation to the Marshall and Palmer. The conclusion can be made that in South Africa the Marshall and Palmer is very adequate in measuring these events.

Stratiform was also stratified using TITAN and a new unique Z-R relation derived.

It is important to note that the new Z-R relation (Figure 4.8) does not have that good a correlation compared to the convective events. Therefore, the Marshall and Palmer would overestimate stratiform events on the Highveld of South Africa.

It can be concluded from the above that the rainfall on the Highveld of South Africa is highly variable over space and time. This makes the improvement of radar rainfall estimates difficult. An attempt was made and relative success was achieved. The most important thing for climatologist is that Africa and specifically South Africa must start moving to dual polarized capabilities of the radars. Capacity building in these radar capabilities is important and once these systems is ion place improving the reliability and accuracy of radar rainfall estimates would be much easier.

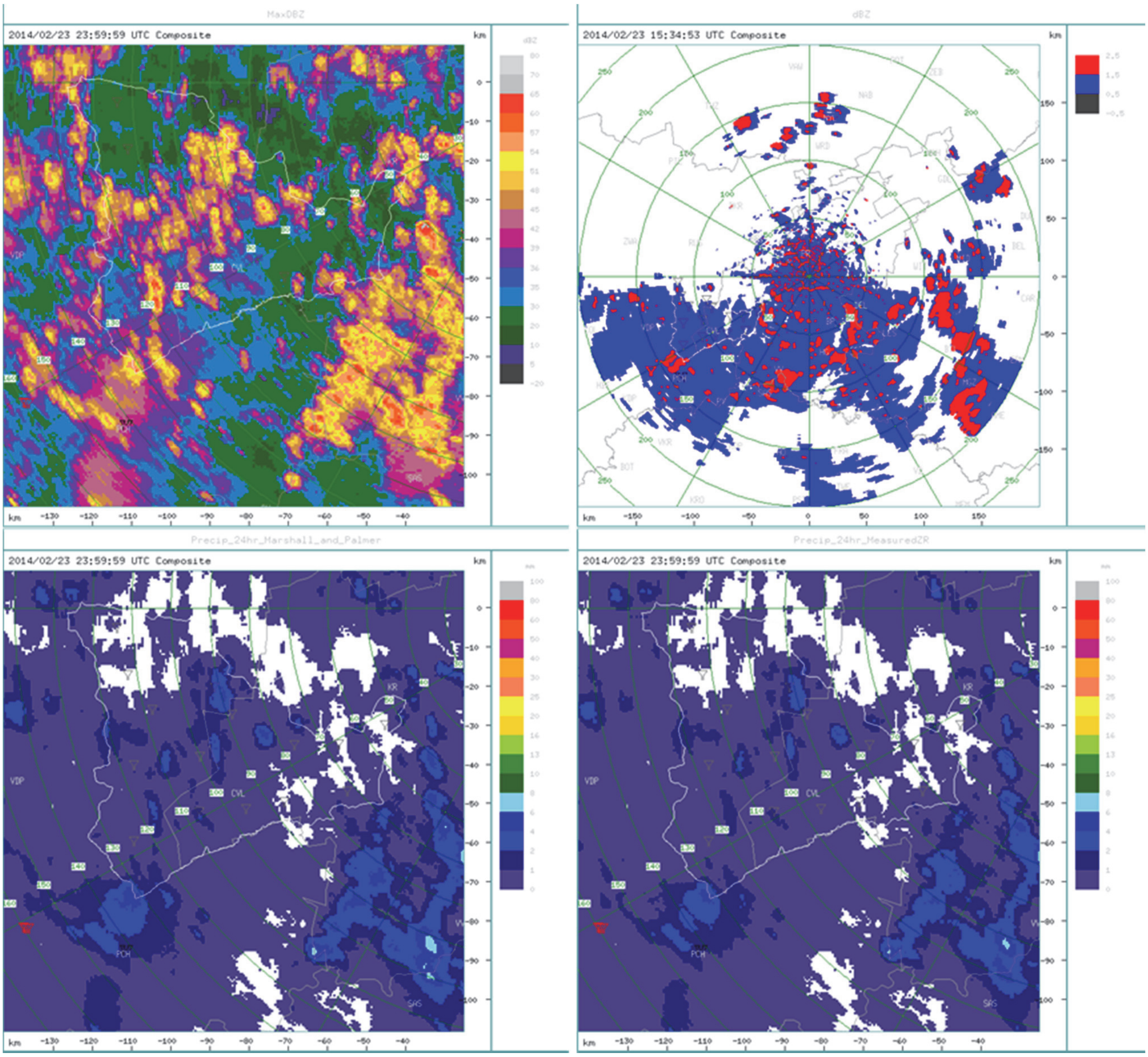


Figure 4.2: Case study 1 of different Z-R relations. Top right: The MaxDBZ for the day. Top left: The stratiform filter program was used to stratify events. Bottom left: The rainfall accumulation using the Marshall and Palmer. Bottom right: The rainfall accumulation measured by the new customized Z-R relation

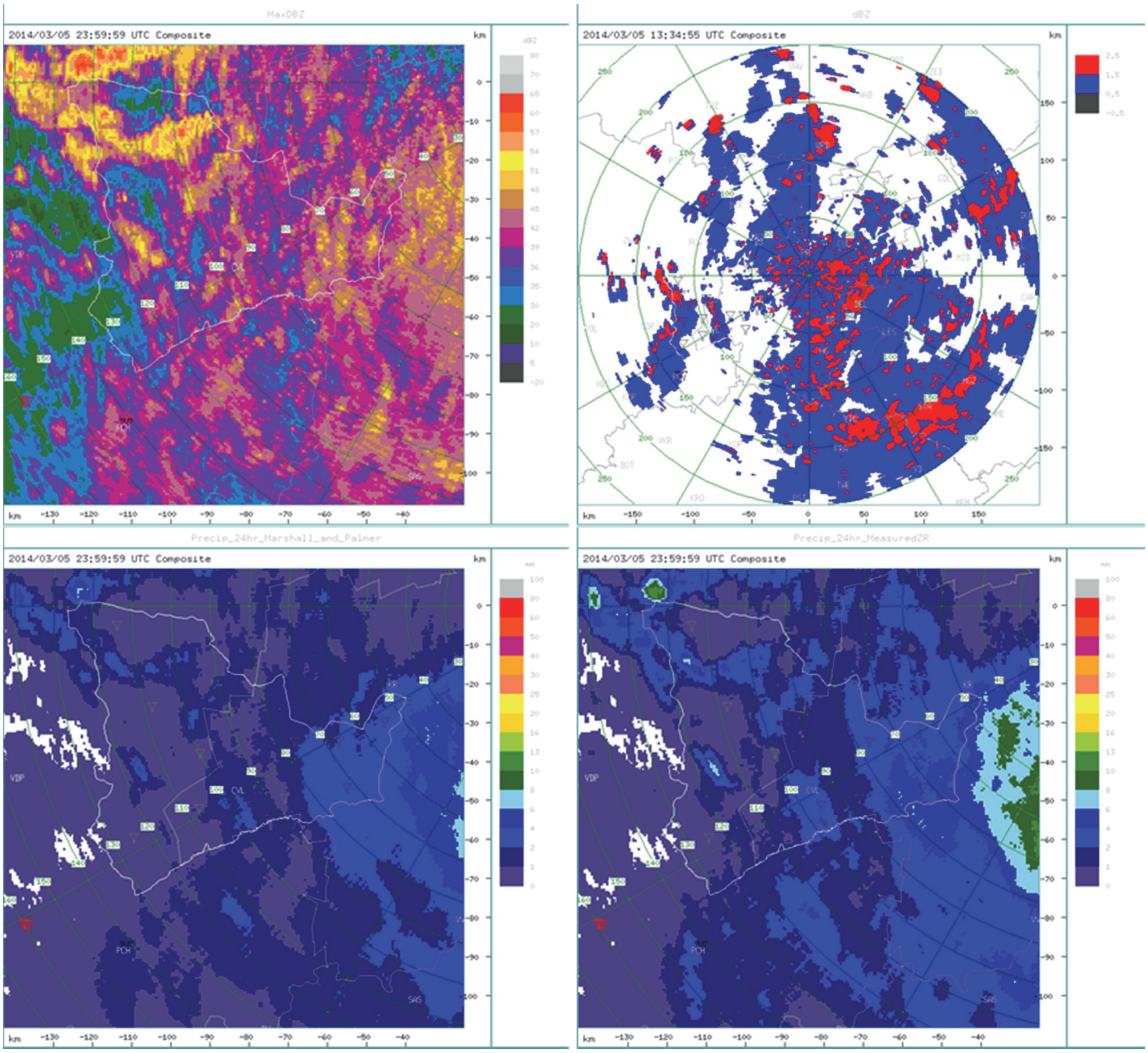


Figure 4.3: Case study 2 of different Z-R relations. Top right: The Max DBZ for the day. Top left: The stratiform filter program was used to stratify events. Bottom left: The rainfall accumulation using the Marshall and Palmer. Bottom right: The rainfall accumulation measured by the new customized Z-R relation

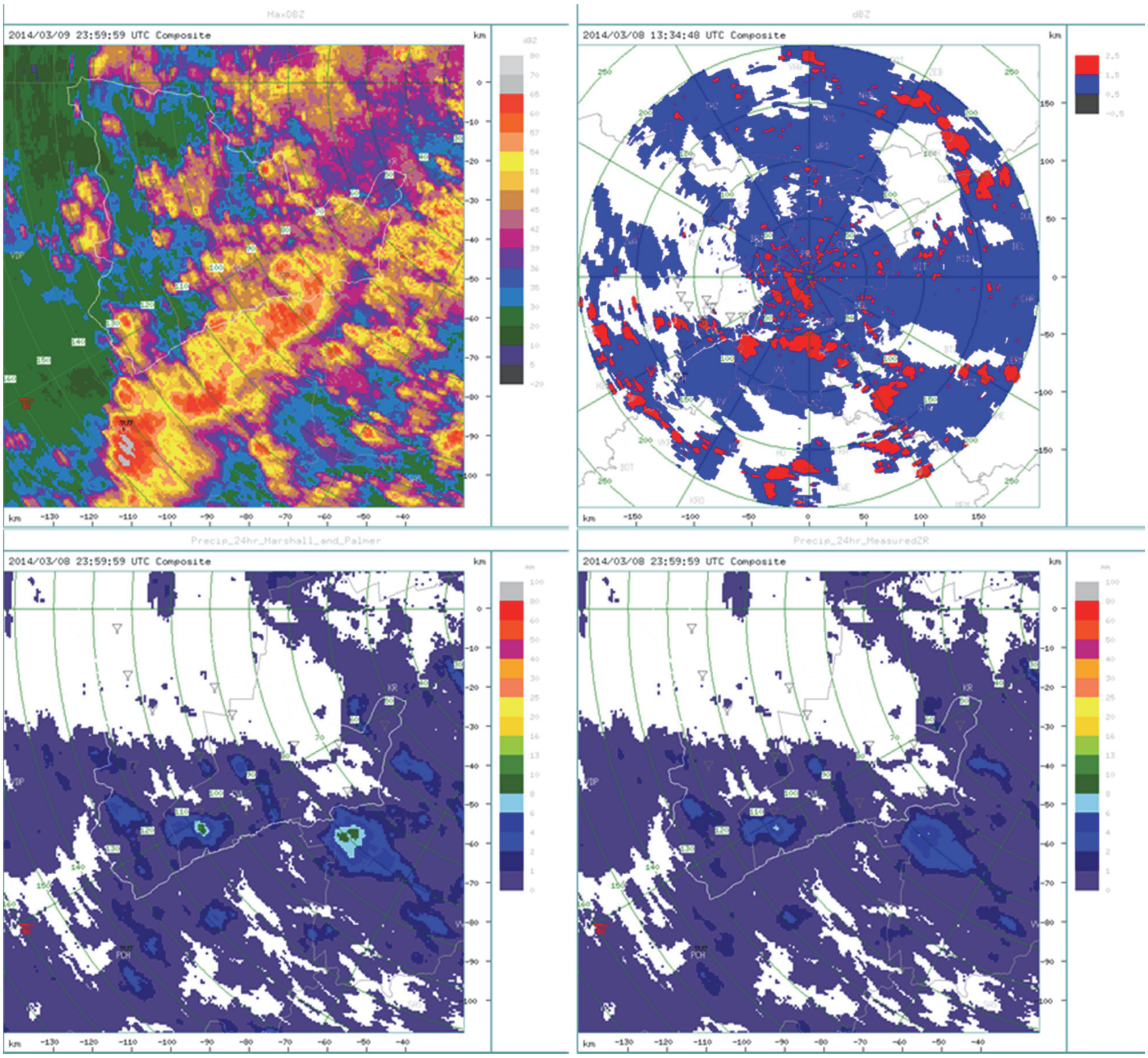


Figure 4.4: Case study 3 of different Z-R relations. Top right: The Max DBZ for the day. Top left: The stratiform filter program was used to stratify events. Bottom left: The rainfall accumulation using the Marshall and Palmer. Bottom right: The rainfall accumulation measured by the new customized Z-R relation.

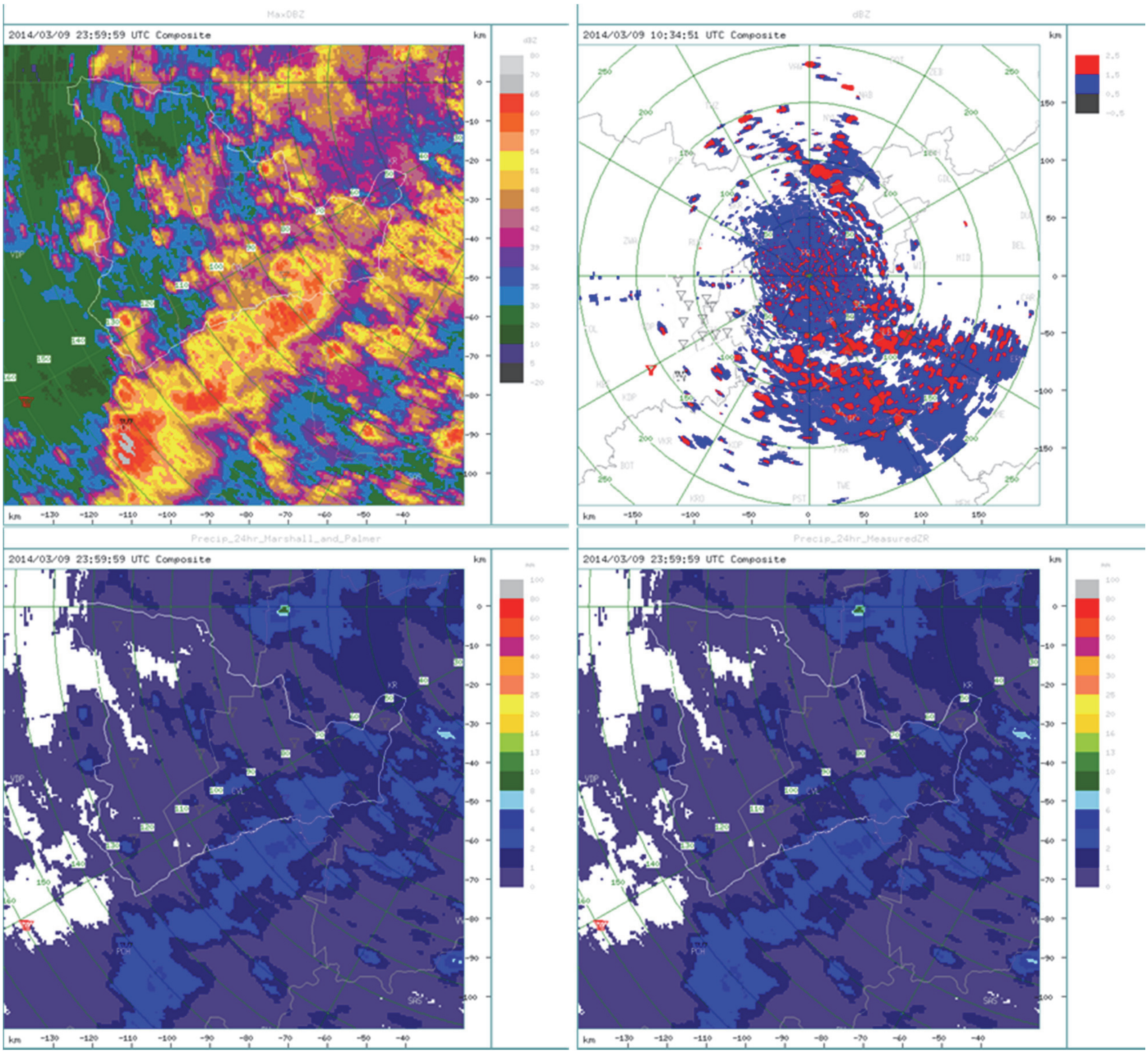


Figure 4.5: Case study 4 of different Z-R relations. Top right: The Max DBZ for the day. Top left: The stratiform filter program was used to stratify events. Bottom left: The rainfall accumulation using the Marshall and Palmer. Bottom right: The rainfall accumulation measured by the new customized Z-R relation.

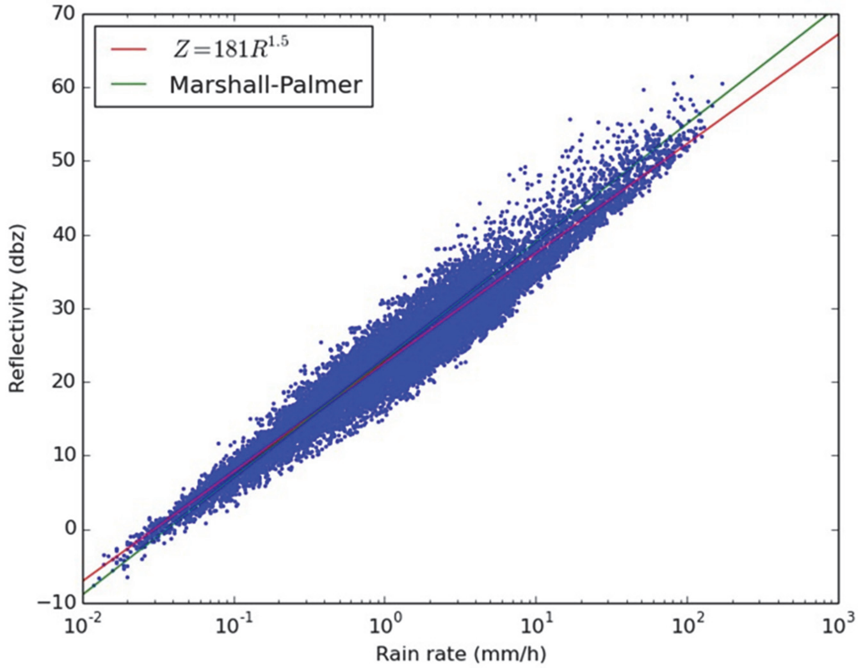


Figure 4.6: The rain rate and reflectivity of the Parsivel compared to each other for all the data from the 21st of February to the 31st of March 2014. This was used to derive a Z-R relation for mixed precipitation.

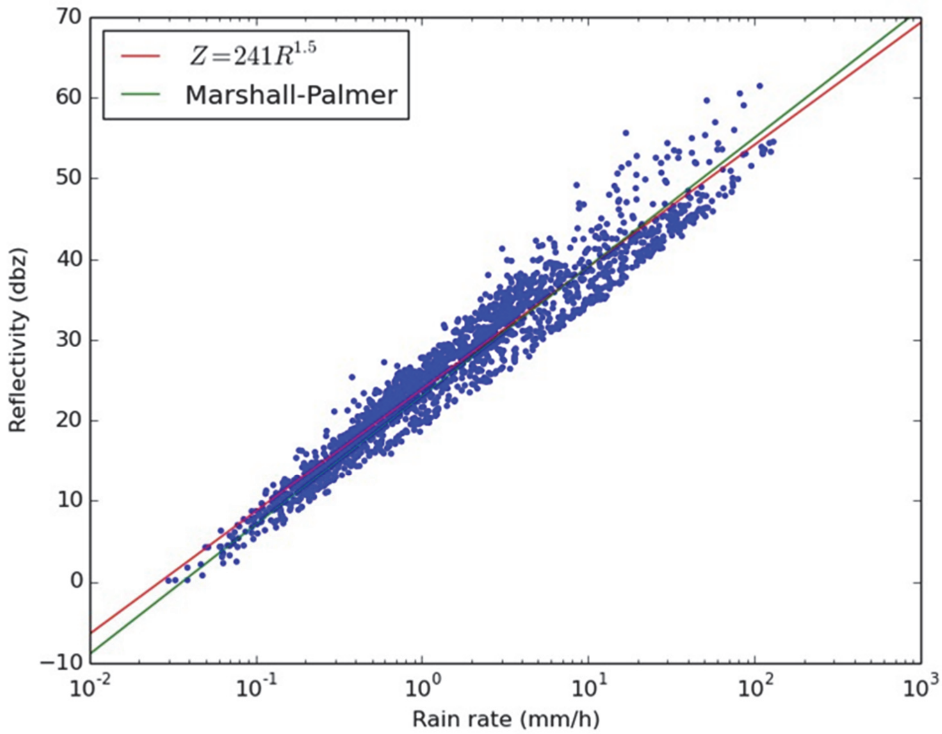


Figure 4.7: Stratiform events identified by TITAN and the rain rate and reflectivity measurements made by the Parsivel compared to each other to derive a new Z-R relation.

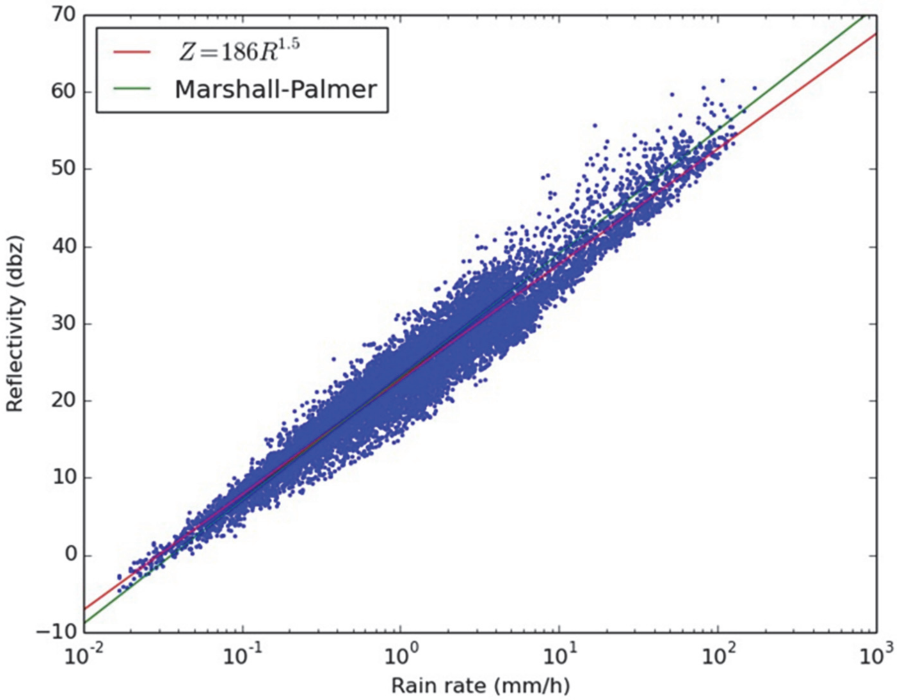


Figure 4.8: Convective events identified by TITAN and the rain rate and reflectivity measurements made by the Parsivel compared to each other to derive a new Z-R relation.

4.2. Stratifying storms into convective and stratiform regimes

Because the Z-R relation between convective and stratiform events differs so drastically it is very important to stratify events. Convective events are characterized by their high rain rate, short, strong horizontal reflectivity gradients and a large vertical velocity duration. These events are normally very localized and has strong up and down drafts whereas stratiform events has lower rain rates, weak horizontal reflectivity gradients, a bright band near the melting layer, weak vertical velocity, longer in duration and is widely distributed (Cui et al., 2007; Houghton, 1968; Atlas et al., 2000).

TITAN has the ability to stratify events into convective and stratiform precipitation. The way this program works is if a pixel is below a certain DBZ values it is classified as a stratiform event and the number 1 is assigned to the pixel. If the DBZ value exceeds a certain threshold it is identified as a convective event and the number 2 is used for these pixels (Figure 4.9).

This is very important to do when an effort is made to improve radar rainfall estimates as the structure of these two types of events differs considerably. Most events that occurs on the Highveld of South Africa is convective events. The correlation between convective storms measured by the radar and ground truth instruments are very good. In some cases, it can be seen that the radar overestimates these events. The reason for this is that at a distance the radar only measured the top part of the storm. The top part is normally where higher dBz values occur but this is not necessarily the case on the ground as factors like evaporation can play a part in decreasing the size of the particle. But this only happens in isolated cases far from the radar and correlation is relatively good. However, radar rainfall estimates of stratiform storms does not correlate that well. This can be because of a number of reasons. Underestimation of these storms is a big problem because at a distance as the beam of the first cappi overshoots low lying events.

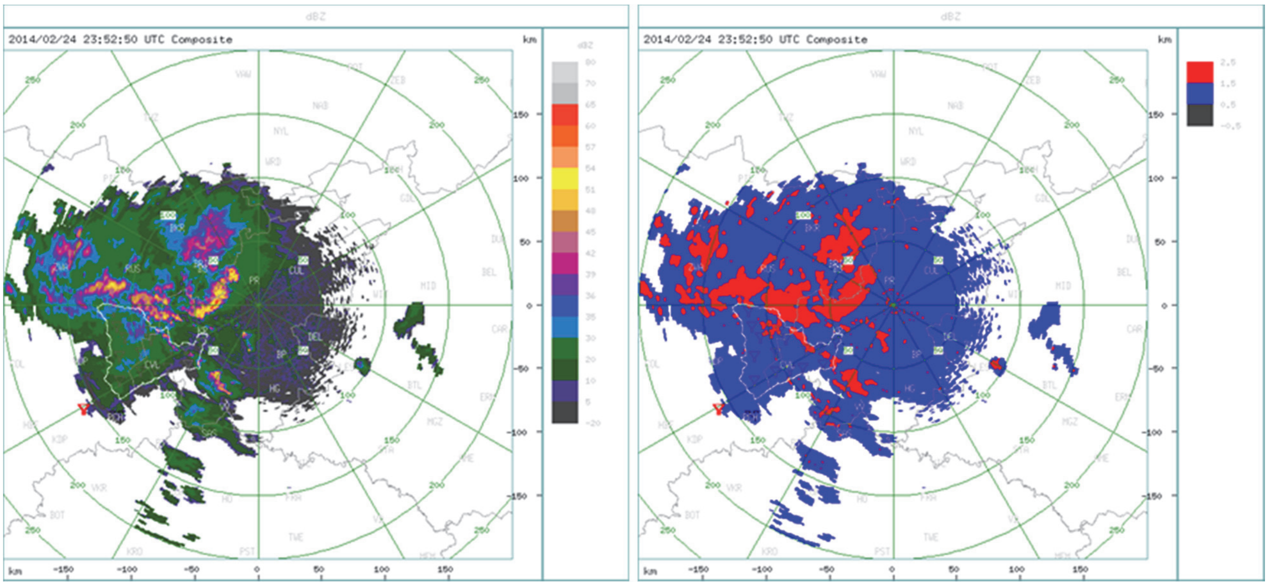


Figure 4.9: Stratiform filter identifies areas were there stratiform and convective rain.

4.3. Deriving rain rates from a Syphon tipping bucket rain gauge

The South African Weather Service operates over 300 tipping bucket rain gauges. Optimizing the Optimal use of these rain gauges is of utmost importance. A high density rain gauge network was installed to develop new and innovative ways to estimate rainfall. This net- work was installed to assist in ground validation of radar rainfall estimates. The Mooi river network is within the coverage are of the Irene weather radar, Bethlehem weather radar and the newly installed NWU Lekwena weather radar.

Using syphon tipping bucket rain gauges possess unique challenges when measuring rain-fall rates. Therefore, this methodology explains step by step a new algorithm to measure rain rates by using a syphon tipping bucket rain gauge. Numerous problems had to be addressed because of the syphon. Firstly, the average time it takes the first 0.2 mm of rain in an event to occur and secondly, syphon rain gauges often cause double tips to in the data.

Changes made to the data often can cause problems. It is therefore important that after each step the cumulative sum of the rainfall must be calculated to eliminate possible mistakes and loss in data. Each tip the rain gauge makes represents 0.2 mm of rainfall. Making sure that the total amount of rainfall stays the same throughout the process is very important. Tips are categorized into two different types namely ED and TD. ED represents a valid tip in an event and TD is a time stamp that helps to determine when the rain gauge is working or not. It is important that a TD tip must not be mistaken with a valid ED tip. Therefore, this algorithm distinguishes between a valid tip and a time stamp by identifying it according to the name.

Because first tips only occur when the bucket has 0.2 mm of rain it is unknown when the event has started which creates problems when measuring rain rates. We used collocated Parsivel disdrometer and rain gauge data to estimate the probability density function of the typical first 0.2 mm of a rainfall event. Events were identified by a 30 min gap between tips. The Parsivel measures rainfall at a high resolution of up to 10 seconds. Combining the Parsivel data with the rain gauge data showed that the average time it takes for the first 0.2 mm of an event to rain is 8.3 minutes. Therefore, the rain rate on average until the first tip is 1.45 $mm.h^{-1}$. By determining the amount of time it rains before the first tip and the difference between tips in the event the rain rate was calculated. The smaller the difference between tips the higher the rain rate of the event.

The data logger used to log the rain gauge data was programmed to give time stamps in the data. This was done to be able to see when the rain gauge is not working. Time stamps occur at 12 o clock in the evening and afternoon every day. But this creates problems in the data as it can in some cases be seen as a tip of 0.2 mm or a start of an event. The algorithm deletes these time stamps that are within 2 hours of valid tips to not have 0 mm of rain inside events.

Rain gauges that use a syphon also have problems with double tips. One of the biggest advantages when using a syphon is that events with high rain rates will not be under estimated allowing a gradual flow of water into the buckets. This, however, can also create a problem because occasionally 0.4 mm of water accumulates in the catchment area. The syphon then dumps this water into the buckets and creates a double tip. This is a problem when calculating rain rates as the time difference between these double tips is often smaller than 4 seconds which will look like an event with a high rain rate. The algorithm solves the double tip issue by identifying the double tip if the next tip is within 4 seconds of the tip and assigning a rainfall amount of 0.4 mm to the first tip. The second tip is then deleted if the previous tip has a rainfall of 0.4 mm and the time difference is less than 4 seconds because the 0.2 mm of rainfall from the second tip has been added to the first tip. The reason why it is very important to delete the second tip is because the time difference between the double tip is very small even if the rain rate of the event is not that high which will cause an error in the accuracy of the rain rate. Data is the resampled to 1 minute, 5 minute, hourly and daily rainfall data. This is done assuming that there is a constant rainfall of 0.2 mm of rain.

5. Knowledge Dissemination and Innovation

Lack of access to data for research is one of the central justifications for this project. Dissemination of the data and knowledge generated as part of this project are therefore key.

5.1. Conference contributions

5.1.1. Contributions during 2012

Benjamin, M. and R.P. Burger (2012). Using Radar and hydrological modeling for flash flood evaluation and prediction. In V. Sivakumar (Ed.), South African Society for Atmospheric Science (pp. 69-71). ISBN: 978-0-620-53375-1. Cape Town.

Benjamin, M. and R.P. Burger (2012). The use of radar and hydrological models for flash flood evaluation and prediction. 3rd WMO/WWRP International Symposium on Nowcasting and Very Short Range Forecasting. Rio. Brazil.

Burger, R.P., Benjamin, M. and S.J. Piketh (2012). Benefits of radar in flash flood prediction. Southern Africa Society for Disaster Reduction. Potchefstroom.

5.1.2. Contributions during 2013

Burger, R.P. and S.J. Piketh (2013). Meteorology and precision farming. Conference on Precision Farming. Potchefstroom.

5.1.3. Contributions during 2014

Botha, T, Burger, R.P., Piketh, S.J. and R. Hauptfleisch (2014). The Impact of Rain Variability on Crop Yield. South African Society for Atmospheric Science. Potchefstroom, South Africa.

Hauptfleisch, R.G., Piketh, S.J. and Burger, R.P. 2014. High density rain gauge network in the North West province. South African Society for Atmospheric Science. Potchefstroom, South Africa.

Van Loggerenberg, J., Piketh, S.J., Burger, R.P and Becker, E. 2014. Evaluating Weather Radar Data by using a ground based Parsivel Disdrometer. South African Society for Atmospheric Science Potchefstroom, South Africa

Van Loggerenberg, J., Piketh, S.J., Burger, R.P and Becker, E. 2014. Evaluating Weather Radar Data by using a ground based Parsivel Disdrometer. African Association for Remote Sensing Johannesburg, South Africa.

5.1.4. Contributions during 2015

Hauptfleisch, R.G., Piketh, S.J. and Burger, R.P. 2015. Optimizing a high density rain gauge monitoring network in central South Africa. South African Society for Atmospheric Science. Johannesburg, South Africa.

Van Loggerenberg, J., Piketh, S.J., Burger, R.P and Becker, E. (2015). Microstructure of rainfall on the South African Highveld. South African Society for Atmospheric Science. Johannesburg, South Africa.

5.2. Data access by the community

The spirit of this project is to share all data with the scientific community. The archived data is distributed with this report. Future projects hope to provide real-time access to rain gauge and radar data through a data server.

5.3. Innovation

5.3.1. The NWU Lekwena radar

With the help of the WRC, the NWU has acquired and installed a second hand C-band weather radar just outside Potchefstroom on the Lekwena reserve (Figure 1). This makes it possible to make three dimensional measurements of precipitating clouds in real-time, every 5 minutes at a 500x500 meter resolution for 200 km around Potchefstroom. Although the South African Weather Service (SAWS) operates 16 weather radars in South Africa, this is the only one fully dedicated to research and capacity building. Commercial pressure necessitates the SAWS radars to sacrifice research quality data for maximum range and continued, reliable operation. The NWU Lekwena radar is therefore an ideal testbed to develop new innovations as well as providing hands-on training. The NWU aims to fill the current void in weather radar capacity in the country by training scientists and engineers in order to make full use of the extensive infrastructure available in the country. We further hope to develop solutions to current South African problems, like upgrading old radars, filtering noise from wireless local area networks from C-band radars and re-engineering old units into multi-parameter radars.

5.3.2. A solid state upgrade for old WSR C-band transmitters

One of the innovations completed on the NWU Lekwena radars is the upgrade of the transmitter. This involved replacing a stack of very old components with current, off-the-shelf technology. The only replacements for some of these old components is from existing international stocks old similar old radar sites. The upgrade therefore makes the radar as a whole much more reliable and extends its lifetime by decades. It also makes the transmitter much more stable and creates the possibility for retrieving additional information from the radar, like Doppler velocities, provided the receiver is also upgraded.

This is the first time that a radar in South Africa received this upgrade. There are currently four SAWS radars that could receive this new technology, as well as numerous old decommissioned radars that could be fixed and redeployed to extend the capabilities of the current national network.

5.3.3. Cheap, versatile loggers

The NWU established a high density network of tipping bucket rain gauges in the Mooi river network between Potchefstroom and Johannesburg to serve the meteorological and hydrological scientific communities. In order to cut costs, a new logger was developed with Electronic Systems Development (ESD) to measure events, analog signals, as well as communicate with instruments using the most common protocols. The logger is produced at a quarter of the cost of the cheapest commercial alternative, the Campbell Scientific E200 used by the Agricultural Research Council (ARC). It further boasts features such as on-board storage on micro SD cards and extremely low power consumption that makes it ideal for this type of research.

5.4. Capacity Building

Capacity and competency development is crucial to the sustainability of the Liebenbergsvlei rain gauge network. Towards this goal, a huge effort is being made to involve as many scientist, students and technicians from SAWS and NWU as possible.

5.4.1. Students working on the project

Table 5.1: Students working on the project to better rainfall estimates from radar

Student Name	Degree	Year	Student nr	ID
Juan van Loggerenberg	MSc	2015	21714355	891120 5095 086
Reinhardt Hauptfleisch	MSc	2015	22449345	890905 5067 080
Ryno Du Preez	MIng	2015	22135928	910125 5077 080
Michael Benjamin	MSc	2015	0510316R	
Nisa Ayob	BSc Hons	2015	23799110	930926 0050 089
Karabo Molapo	BSc Hons	2015	24011479	900522 6102 085
Thalita Botha	BSc Hons	2014	22301240	911111 0074 081
Henno Havenga	BSc Hons	2014	22743529	920603 506 1088
Keorapetse Moeketsi	BSc Hons	2016	23526130	931121 0274 082

5.4.2. Institutional development

With the establishment of rain gauge networks for radar validation, better rainfall radar estimations will result. This improved radar data will be utilised at NWU to build on remote sensing knowledge as well as implementing a new post graduate research facility where students can enhance their learning and in turn acquire skills and build capacity.

Improved rainfall estimation will greatly benefit SAWS with better predictions and improved warnings for flash floods and hail storms can be initiated and sent to vulnerable communities.

Radar installation workshop

During the installation and testing of the North-West University's Lekwena radar, a workshop was hosted for employees of the South African Weather Service. This workshop contained practical examples on how to install a C-band weather radar. The following aspects were illustrated throughout the workshop:

- Installation and levelling of the transmitter and waveguide.
- Installation and levelling of antenna pedestal.
- Installation of RDAS2k communication system with control unit for remote access.
- Start-up and shutdown procedure.
- Measuring peak output power, duty cycle, pulse width and the PRF.
- Levelling of antenna dish according to the suns position.
- Calibration techniques and connection diagrams.
- Practical troubleshooting on possible problems as slip-rings and bushings.

The workshop was a success and much was learned throughout the workshop.

5.4.3. Community Development

With the introduction of the state-of-the art radar systems, new tools and data utilised at tertiary education level will benefit students and provide them with the skills to take them into the working world.

The new radar network cover most of South Africa. This will ensure the ability to develop early warning systems for all major population areas. Vulnerable communities most benefited from enhanced early warning systems that could result from improved real-time rainfall estimation.

6. Conclusions and Recommendations

Weather radar is an unparalleled tool to study and quantify storms and precipitation. South Africa is equipped with state of the art infrastructure. However, capacity and resources are lacking. An effort is underway to establish a center of excellence in observing precipitation. The high density rain gauge network, the optical disdrometer and the Lekwena radar forms the backbone of these activities. The infrastructure provides access and data to the South African scientific community. A data set from a high density rain gauge network has been gathered for the 2014-2015 season.

The life of old Enterprise radars can be extended by re-engineering obsolete components. The transmitter of the Lekwena radar was successfully replaced using the off-the-shelf solution produced by Pulse Systems Inc. This upgrade can benefit four current and six decommissioned SAWS radars.

A custom designed low power logger was developed for rainfall estimation. These loggers can also accommodate soil moisture and analog measurements. They are ideal for large, cost-effective networks like the Mooi river catchment.

South Africa still does not use its weather radar infrastructure to its full potential. These efforts aimed to build capacity and resources to stimulate interest and research around the use of weather radar for precipitation estimation.

6.1. Capacity building on radar estimates of rainfall

Capacity building in weather radar remains a primary concern. Workshops, training sessions, and access to operational radars need to be prioritized.

6.2. Access to research quality data

Access to data for research purposes is restricted. The pressures of limited resources and a commercial environment put science on a low priority. The infrastructure developed as part of this project provides research grade data to the scientific community. It is our hope to continue building this as a national resource. Data is the primary resource for research into weather radar. The Mooi river network can serve a wide community and therefore stimulate product development and the use of weather radar in applied science.

6.3. Automation of the Mooi river network

The rain gauge network is currently not automated. Low power modems need to be developed to transmit data to a central server. Real-time data will open up new possibilities and application of the data captured in the Mooi river network.

6.4. Increasing the density of the Mooi river network

The current network density of the rain gauges can still be improved. The spatial variability cannot be sampled at spatial scales less than 20 km and temporal scales less than 12 hours. Increasing the density will make it possible to study additional research problems.

6.5. Re-engineering the NWU Lekwena radar receiver

A modern radar receiver will make it possible to extend the life of approximately 8 old weather radars in South Africa. The technology for this upgrade has been identified and the Lekwena radar can be used as a test bed for the new receiver.

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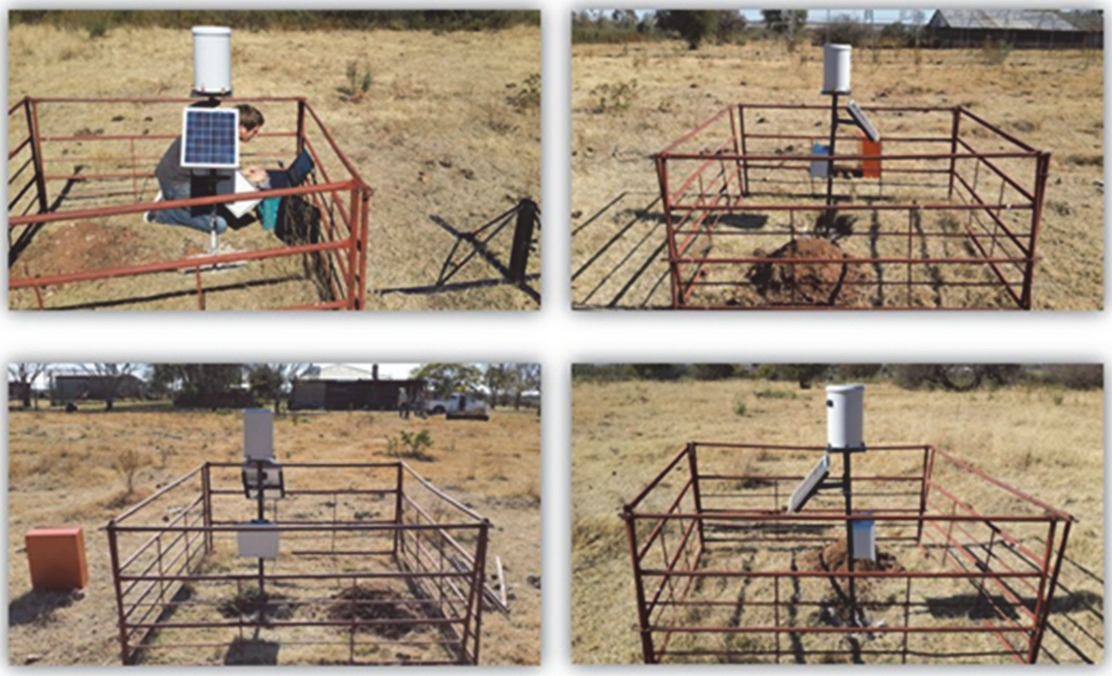
Appendix A: Description of sites



Site 1 at Farm – Muiskraal (27.11288, -26.44093)

Site 2 at Farm Wolwefontein (27.11478, 26.26621)

Site 3 at Laerskool De Beer (27.27971, -26.375)

Site 4 at Farm – Doornfontein (27.52446667, -26.22258)

Site 4 at Farm – Doornfontein (27.52446667, -26.22258)

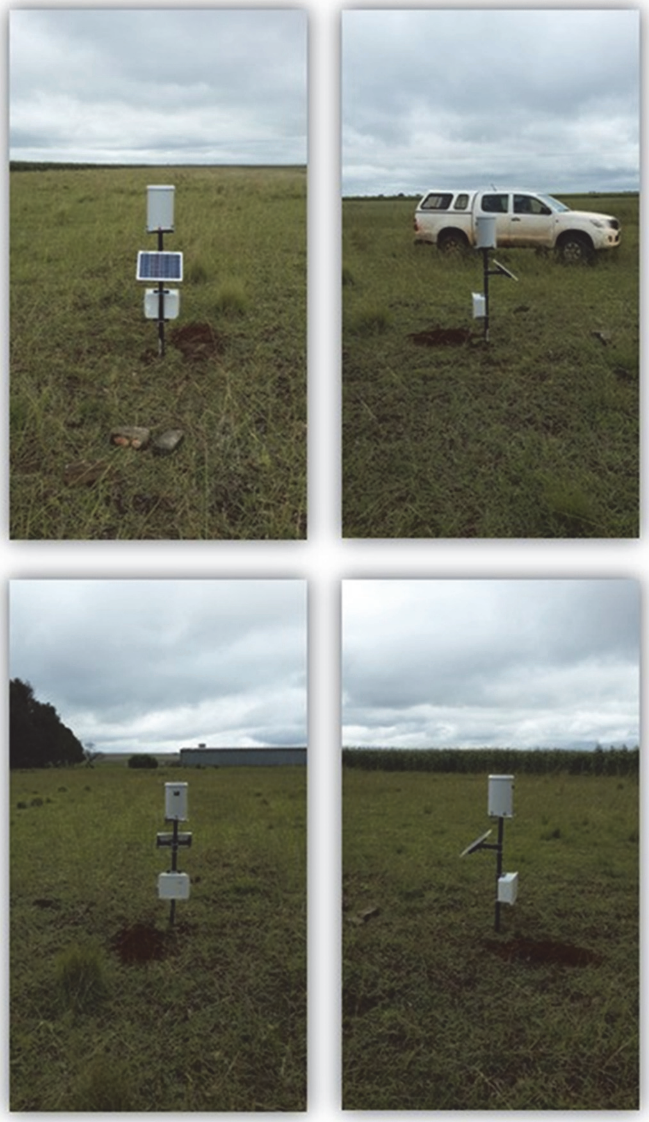
Site 5 at Hoërskooll Westonaria (27.6598, -26.32908)

Site 5 at Hoërskooll Westonaria (27.6598, -26.32908)

Site 6 at Farm – Rooibees (27.10115, -26.05958)

Site 7 at Farm – Leriana (27.36545, -26.15192)

Site 8 at Farm – Vlakfontein (27.07291, -25.95125)



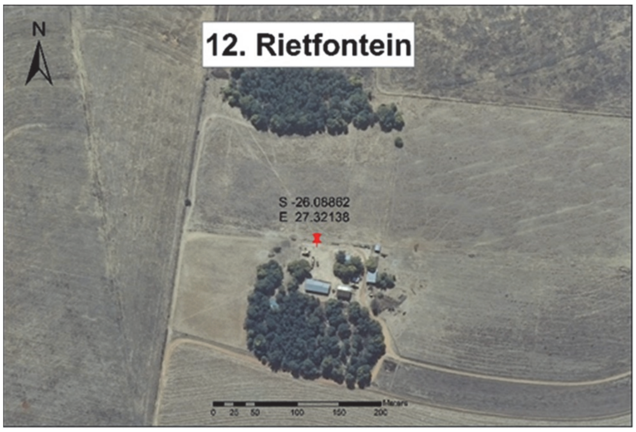
Site 8 at Farm – Vlakfontein (27.07291, -25.95125)

Site 9 at Farm – Leeuwpan (27.28291, -26.2486)

Site 10 at Carlton Jones High School (27.39984, -26.36755)

Site 11 at Randfontein Boerbulls (27.63801, -26.22113)

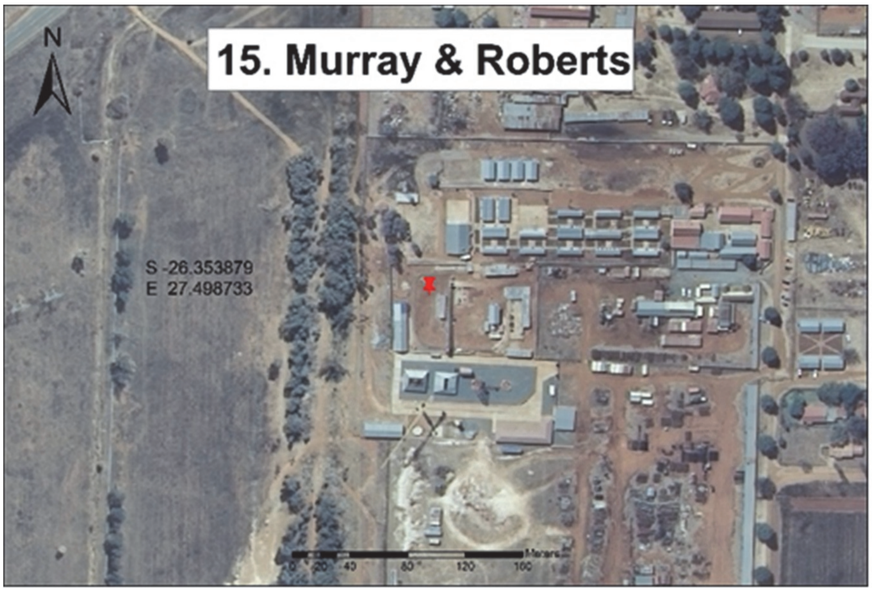
Site 12 at Farm – Rietfontein (27.32138, -26.08862)

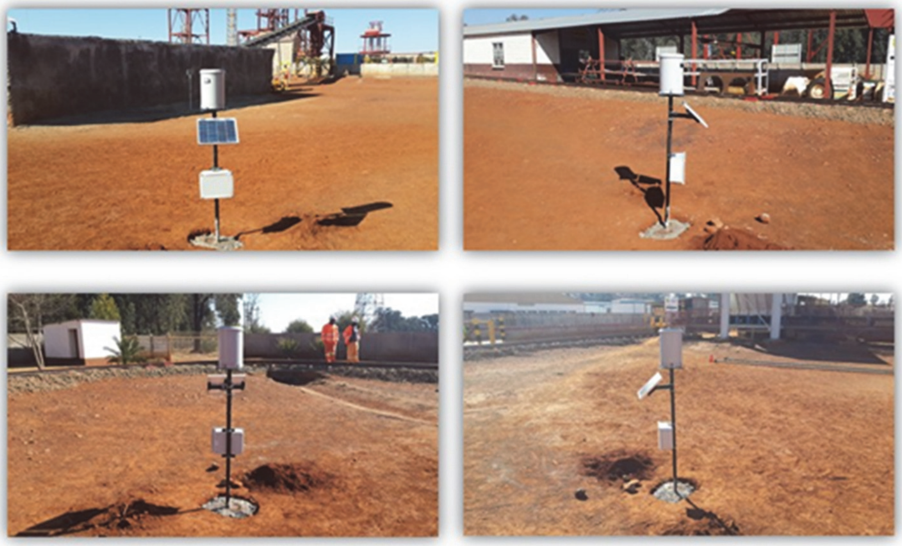


**Site 12 at Farm – Rietfontein (27.32138, -26.08862)**

Site 13 at Farm – Klipgat (27.16119, -26.13857)

Site 14 at Madrasah Arabia Islamia (27.7574,   -26.17812)





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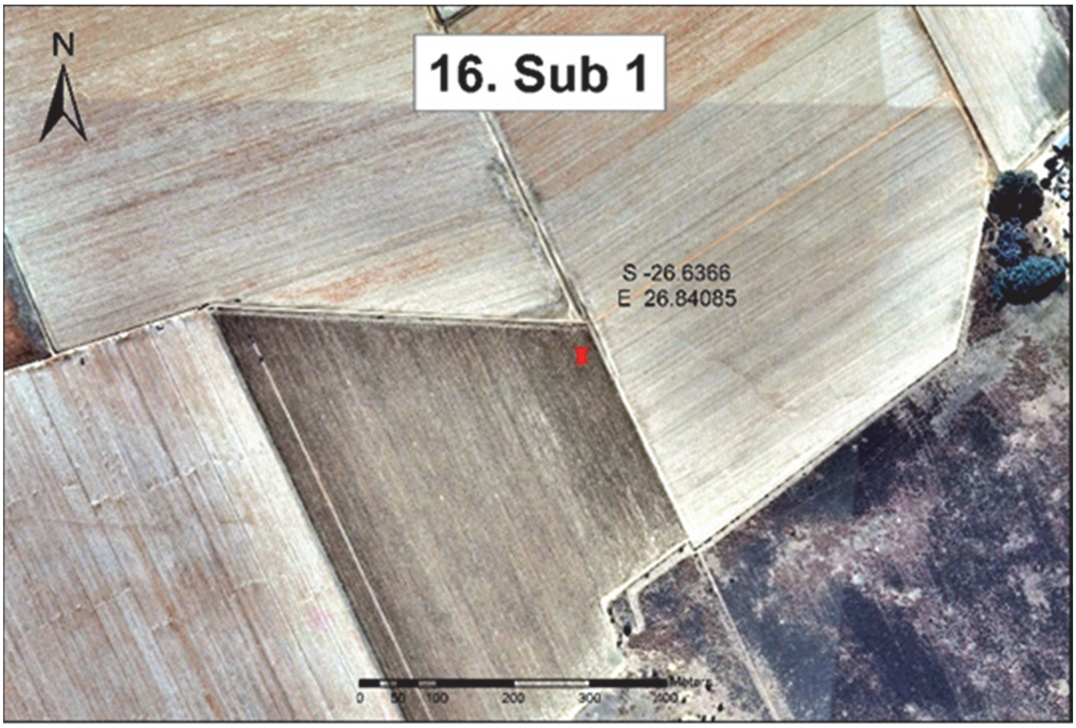
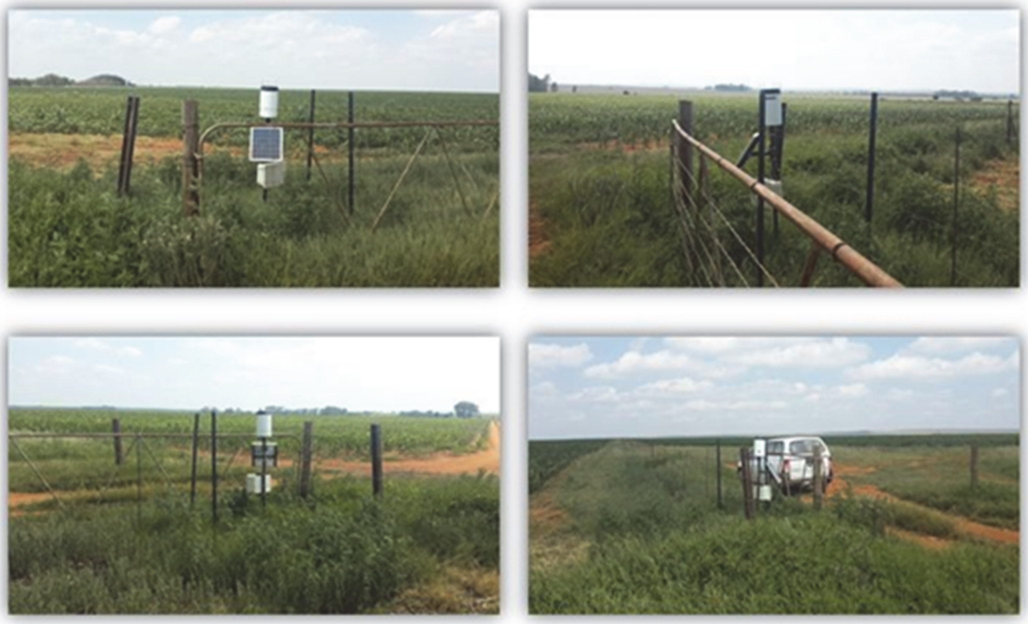
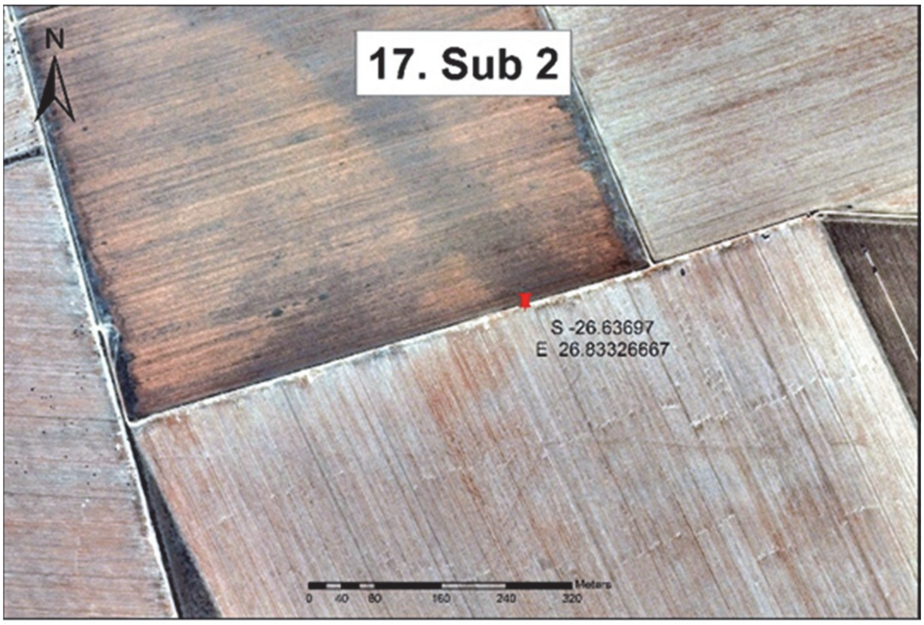
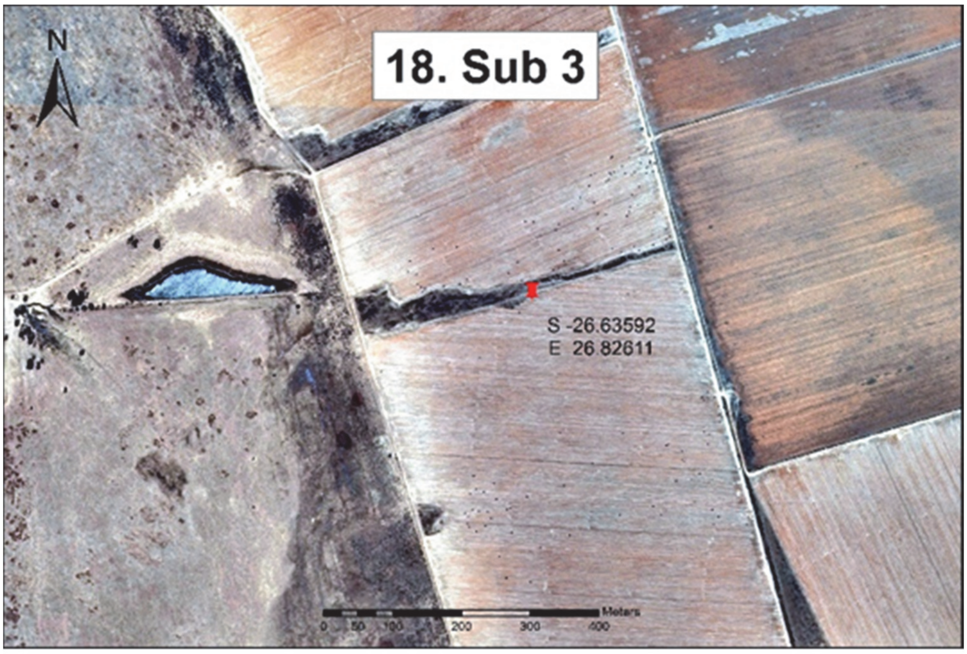




Site 16 at Keet Boerdery (26.84085, -26.6366)



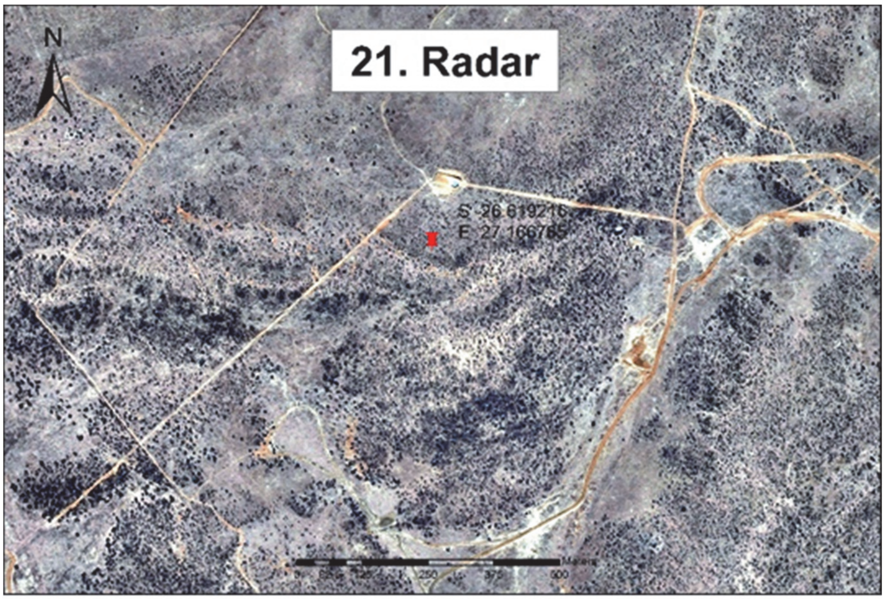
Site 17 at Keet Boerdery (26.83326667, -26.63697)



Site 18 at Keet Boerdery (26.82611667, -26.63592)

Site 19 at NWU building E4 (27.09055, -26.68968)

Site 20 at NWU Botanical Garden (27.095546, -26.681918)



Site 21 at NWU Lekwena weather radar (27.166785, -26.619216)