

Characterising rainfall using a high density rain gauge network in the Mooi River catchment

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ABSTRACT

Understanding and measuring rainfall is of critical importance for agriculture, disaster mitigation, drought relief and water resource management practises. With the advancement of technology, methods of earth observation have greatly improved. Satellite and weather radar can provide high resolution real-time measurements of rainfall. These instruments, however, need calibration and ground validation which can be accomplished with rain gauges. Therefore, the need to better understand and characterise spatial variability of rainfall using a rain gauge network is of great importance. The objectives of this study was, firstly, to evaluate the use syphon tipping bucket rain gauges to accurately characterise rainfall, secondly characterise the spatial variability of rainfall with a high density rain gauge network and finally to optimise the high density rain gauge network. A dense network of 15 syphon tipping bucket rain gauges spread out over the 3294 km² Mooi River catchment in the North West and Gauteng provinces of South Africa, was used to characterise rainfall for the 2014/2015 rainfall season. Methods to evaluate the use of syphon tipping bucket rain gauges to determine the spatial variability of rainfall and to optimise a rain gauge network are described. Because tipping bucket rain gauges can produce misleading reports, this study suggests easily programmable diagnostic check that can be used in an operational environment to identify and eliminate any errors associated with rain gauge data. These checks were tested on the data obtained from the rain gauges in the Mooi River catchment and a variety of confirmed errors were found. The spatial variability of rainfall over the catchment was defined for rainfall accumulation periods ranging from 1 min to 14 days. It was evident that rainfall exhibits high spatial variability at shorter accumulation periods between 1 and 30 min with very poor correlation between gauges even at the shortest separation distances of 8 km. For longer accumulation periods, the daily scale for example, there is a good correlation between all the gauges of the network, even at 80 km separation distances. Therefore, the current rain gauge network in the Mooi River catchment is dense enough to provide information of rainfall at a daily resolution, but when high resolution rainfall data at a finer time scales are needed (e.g. 5-minute accumulations), the network is not dense enough. In order to accurately estimate the spatial variability of rainfall, a dense network of instruments is required, which will typically entail large installation and operational costs. Therefore, it is essential to optimise the number and distribution of rain gauges in a network. This in turn will make it possible to better estimate the rainfall at unrecorded locations from data recorded by an existing network of rain gauges. The optimal distribution of gauges for the Mooi River catchment was determined using a set of rules based on ordinary kriging error variance to assess the accuracy of rainfall estimation. Based on these rules, the total area in the network with acceptable estimation accuracy can be calculated. This study proposes a method to prioritise the existing rain gauges in the network, as well as identifying

additional sites where rain gauges could be installed in order to improve the estimation accuracy of the Mooi River catchment rain gauge network. It was found that the current network of 15 rain gauges in the Mooi River catchment is not dense enough for high resolution rainfall estimates and an additional 13 rain gauges should be added to the existing rain gauge network. A total of 28 rain gauges are therefore required in the augmented network in order to obtain as much surface coverage of gauges over the catchment with acceptable accuracy as possible. The study contributes a great deal of knowledge to the scientific field through: a unique high-resolution rain gauge network. A new method of data quality control for syphon tipping bucket rain gauges is proposed. A better understanding and estimation method of the spatial variability of rainfall as well as a method to establish the optimal density of gauges in a network to capture the spatial variability of rainfall has been established.

Keywords: *Rain gauge data quality control, Optimal rain gauge network design, Rainfall variability, Rainfall estimation Kriging, Geostatistics*

PREFACE

The research contained in this dissertation was completed by the author between 2014 and 2015 while based in the Discipline of Geography at the School of Geo and Spatial Sciences of the Faculty of Natural Sciences, North West University, Potchefstroom, South Africa. The research was funded by the Water Research Commission (WRC).

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

Rainfall data that is complete and accurate is indispensable for many hydrological analysis and design projects. High resolution rainfall estimates are used for, the prediction of catchment responses, agricultural planning, and in water resource management. Rainfall is however highly variable at both spatial and temporal scales. Thus, for the accurate estimation of the spatial distribution of rainfall, a high density of instruments are required, which usually entails large installation and operational costs. To account for the spatiotemporal variation of rainfall, there are several advance approaches such as radar, satellite and numerical weather prediction models. However, these instruments require validation and calibration with measured rainfall data from rain gauges.

Rain gauges are considered to make very accurate estimates of rainfall and rain gauge networks are generally used to provide measurements which characterises the spatiotemporal variation of rainfall. However, even though rain gauges can provide rainfall estimates in real time at very high resolution in time, the spatial variation of rainfall is still difficult to determine without a dense network of rain gauges.

High density rain gauge networks are expensive to maintain and operate and the South African rain gauge network is in decline and the current economic situation in South Africa does not help the situation. Thus, there is a need to optimise the available rainfall monitoring infrastructure that is currently in operation around the country. The Liebenbergsvlei network provided a valuable dataset between 1994 and 2000 that has been widely used by the scientific community. Remote sensing technology has greatly improved in the last decade. A new, state-of-the-art radar network was installed in South Africa between 2009 and 2013. Satellite estimates of rainfall has also seen great advances as seen by the work of the International Precipitation Working Group. However, now high resolution rainfall data is currently available. The WRC funded this work to establish a network on the Highveld.

This study has been conducted in the Mooi River catchment situated in the Highveld of South Africa. High resolution rainfall estimates will especially be beneficial to this region because; It is the economical heart of South Africa, the region has a very high population density that are vulnerable to changes in rainfall, and there is a large number of agricultural activities practised in this area which rely on accurate rainfall information for their wellbeing.

The goal of this research is to characterize rainfall using a high density rain gauge network in the Mooi River catchment, with specific objectives being:

1. Evaluate the use of syphon tipping bucket rain gauges to characterise rainfall.
2. Characterise the spatial variability of rainfall in the Mooi River catchment.
3. Optimise rain gauge network density for the South African Highveld using the Mooi River catchment as a case study.

The remainder of this document describes the steps taken to address each of the research objectives and the results.

In Chapter 1 the general characteristics of rainfall and the measurement thereof is discussed. Specific attention is given to what is said in literature on the uses of rainfall data, what methods there are for estimating rainfall, the variability of rainfall over space and time and the optimisation of rainfall monitoring networks. Chapter 2 describes the, installation and maintenance process of the high density rain gauge network in the Mooi River catchment, the quality control of the Mooi River network data, and the data analysis procedures used to achieve the above objectives. Chapter 3 interprets the results of the data quality control process with syphon tipping bucket rain gauges. Errors in the data such as questionable high rain rates and partial blockages of rain gauges are identified using automated quality control algorithms. In Chapter 4 the spatial variability of rainfall in the Mooi River catchment is characterised using historical rainfall data obtained from South African Weather Service (SAWS) as well as data obtained from the high density rain gauge network in the Mooi River catchment. Chapter 5 presents the results of the optimisation of the high density rain gauge network in the Mooi River catchment. And lastly, Chapter 6 gives a summary and conclusion of the methods and results presented in this study.

Some of the sections in this dissertation have been published and presented both orally and in poster format at the conferences of the South African Society for Atmospheric Sciences (Potchefstroom, South Africa, 1-2 October 2014 and Pretoria, South Africa, 21-22 September 2015).

The author was personally involved with the conceptualisation, installation, maintenance, and data collection of the high density rain gauge network in the Mooi River catchment throughout the study period. Assistance during the installation and maintenance of the network was received from Mr. Richein du Preez, Mr Joe Malahlela and Mr Jaun van Loggerenberg.

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As I approach the end of my studies at the North-West University, I would like to take a moment and look back at how far I have come in the past six years and thank those who have helped me along the way. The summit of this long journey has now come within reach and I am thrilled to finally arrive. Indeed, our time on this glorious summit of life is short-lived and new mountains are waiting to be conquered. From this summit though, I have a clear view of the ascent and an enormous appreciation to all those who have helped me achieve my goals throughout this journey. To my family, friends, and mentors, I cannot thank you enough for your guidance and support. These past six years at the North-West University have been the best time of my life.

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ABBREVIATIONS

ARC:	Agriculture Research Council
CSV:	Comma-Separated Values
DSD:	Drop Size Distribution
DWS:	Department of Water and Sanitation
ENSO:	El Niño-Southern Oscillation
ESD	Electronic Systems Development
EVAC	Environmental Verification and Analysis Center
GPRS	General Packet Radio Services
GSM	Global System for Mobile
IDW	Inverse Distance Weighted
ITCZ	Inter Tropical Convergence Zone
MAD:	Median Absolute Deviation
MRGN:	Mooi River Rain Gauge Network
RMSE	Root Mean Square Error
SA	South African
SAST:	South Africa Standard Time (UTC +2:00)
SAWS:	South African Weather Service
SD:	Secure Digital
SST	Sea Surface Temperatures
TBR:	Tipping bucket rain gauge
TITAN	Thunderstorm Identification Tracking Analysis and Nowcasting
UTM	Universal Transverse Mercator
WMO:	World Meteorological Organization
WRC	Water Research Commission

This dissertation is dedicated to my Parents

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and

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CHAPTER 1 INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

The distribution of rainfall over the earth's surface is one of the most important and widely recorded parameters in the global hydrological cycle (Legates & Willmott, 1990; Kozu et al., 2008). The hydrological cycle distributes water over the earth's land and oceans as precipitation. Precipitation comes in various forms, such as rain, snow and hail. The most common type of precipitation in South Africa is rainfall. Rainfall measurements are essential for many scientific applications in the fields of meteorology, hydrology and agriculture and other environmental sciences and it is becoming ever more important in these fields to get detailed estimates of rainfall for both spatial and temporal scales (Frezghi and Smithers, 2008; Ghile et al., 2010; Savina et al., 2012). Rainfall is, however, a dynamic process that frequently changes in form and intensity as it moves over a certain area on the earth's surface. This makes it difficult to measure over space and time (Jensen and Pedersen, 2005; Biagorria et al., 2007).

South Africa is a water scarce country with an average rainfall of about 450mm (Otieno and Ochieng, 2004; Muller et al., 2009). The low rainfall is a direct consequence of the highly variable climate, which makes South Africa very vulnerable to water shortages. 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. Very little of moisture brought with the atmospheric systems moving over South Africa ends up as precipitation on the ground (Shippey et al., 2007). Rainfall in South Africa commonly occurs in the form of convective storms which are spatially and temporally highly variable and these type of events can potentially cause flash flooding, hail and other storm-related damage which can have a severe impact on human life and the economy, especially in highly populated places (Molini et al., 2005). Thus, the need for measurement of rainfall is critical for a country such as South Africa.

Direct rainfall measurements are commonly made with rain gauges that are installed as a network to provide rainfall measurements with which the spatial and temporal variation of rainfall over an area can be characterized. Data obtained from rain gauge are considered to be very reliable and have a high degree of accuracy at a point (Martens et al., 2013). However, even though rain gauges with tipping buckets or distrometers can give real time rain rates with a high temporal resolution, the spatial variability of rainfall is still difficult to characterise without a rain gauge network with high enough spatial density (Villarini et al., 2008 and Cheng et al., 2008; Li et al., 2014).

Remote sensing of rainfall offers an alternative approach to characterise the spatial variability of rainfall over large areas. With remote sensing rainfall can be observed from a distance with a

limited infrastructure footprint. Recent advances in the field of remote sensing have given scientists the ability to obtain information of rainfall with greater spatial coverage than ever before. Remote sensing of rainfall is generally done with weather radars and satellites. These instruments can provide rainfall measurements in near real time with exceptional spatial coverage (Wilson and Brandes, 1979; Browning et al., 1982). Radar and satellite measurements, however, cannot provide rainfall estimates to match the accuracy that is achieved by rain gauges. The algorithms used by these instruments for estimating rainfall must be calibrated and validated using rain gauge networks. Thus, the merging of rain gauge data with either of these two remote sensors in order to achieve the most accurate estimates of rainfall has become common (Steiner et al., 1999; Sinclair and Pegram, 2005; Tokay et al., 2010).

The siting of rain gauges is determined by various factors, such as accessibility, maintainability and topography. Furthermore, the minimum density of a rain gauge network is determined by the functional objective that the data will be used for. It is important to properly evaluate the performance of an existing network and if necessary, augment the network in order to achieve the desired time resolution of rainfall measurements as required by the objective of the network. Such an evaluation will give an indication of the extent to which the current network is equipped to handle the spatio-temporal variability of rainfall that it has to measure and also to what standard the quality of the data is that the network provides.

Thus, the main goal of rain gauge network optimisation is to achieve the most reliable and accurate estimates of rainfall. Most rain gauge network optimisations are primarily focussed on reducing error variances of radar based rainfall measurement, but not that of point rainfall over the area of interest. Radar rainfall estimates may be sufficient input for most applications, such as, water resource management or general agriculture, but for applications such as flash flood forecasting and precision farming, monitoring localised high-intensity rainfalls becomes extremely important. Therefore, focussing on the estimation accuracy of point rainfall measurements is immensely important in the evaluation and optimisation of a rain gauge network.

This study is aimed at exploring the spatial variability of rainfall over the South Africa Highveld during the summer rainfall season of 2014/2015. To put this into context, the body of work surrounding ground-based rainfall measurements, using rain gauge network's is explored and methods to improve rainfall measurements using these instruments are investigated. Furthermore, the rainfall over South Africa and the spatio-temporal variability thereof will be presented.

1.2 Literature review

Many attempts have been made to quantify rainfall at catchment scale in both space and time through the use of areal averaging techniques. There is a rich history of work reported in literature on the characterization of rainfall by depth, duration, intensity and frequency. The spatiotemporal variability of rainfall has also been investigated by many studies using dense rain gauge networks, weather radars and satellites. However, there is a shift from ground based measurements to remote sensing that is happening globally. South Africa is no exception and the number of rain gauge reporting stations and quality of data has been declining. Thus, there is a need to look at new and effective ways of optimising our current rainfall measurement infrastructure.

1.2.1 The general characteristics of rainfall in South Africa

In order to understand the characteristics of rainfall, it is important to know how it forms. Rainfall forms when evaporated water in the atmosphere condensates to form clouds. This phase transition of water from vapour to a solid state plays a crucial role in the formation of clouds and rainfall (Korolev & Mazin, 2003). Clouds contain millions of miniscule water droplets that are suspended in the air by updrafts in the cloud. When a cloud becomes saturated, all these droplets begin to collide with each other and grow. Once the drops grow too large and heavy for the updrafts of air to support them, they start to fall to the ground as rain (Tyson & Preston-Whyte, 2000).

This process of cloud formation to eventual precipitation is the result of a multitude of interactions within the cloud that range from cloud-aerosol interactions at the microphysical scale, to the interaction of a single cloud with the dynamic and thermodynamic properties of a larger scale environment. Rainfall is subjected to various microphysical processes on its path from cloud formation to eventually reaching the ground. These processes typically include coalescence (warm processes), ice aggregation (cold processes), collision, breakup and evaporation. These microphysical processes play a significant role in each type of rain that occurs at various altitudes, ranging from heavy intensity rainfall produced by convective systems to low intensity rainfall from stratiform systems (Lensky & Rosenfeld, 2003; Konwar et al., 2014).

Clouds and the rainfall derived from them, are some of the most important drivers of atmospheric circulation. The energy that is absorbed by the earth's atmosphere is predominantly derived from latent heating which is a result of the condensation process, where water vapour is turned in to precipitation. Most of the rainfall events that occur in South Africa can either be characterised as convective or stratiform systems. Convective systems are generally associated with strong updrafts and downdrafts that are localized and have high intensity rainfall (Visser & Van Heerden, 2000; Gill, 2008; De Coning & Poolman, 2011; De Coning, 2013; Dedekind et al, 2016). Stratiform

systems on the other hand are more horizontally homogeneous with weaker updrafts and downdrafts and low rainfall intensities. Due to these differences the two systems have different latent heating profiles and therefore the earth's climate is impacted differently by each system. Convective systems heat the atmosphere through the condensation of water vapour, and stratiform systems cool the atmosphere through the evaporation of raindrops within the system (Arkin & Meisner, 1987; Levin et al, 1996; Anagnostou & Kummerow, 1997; Hong et al, 1999).

When investigating the climate, it is evident that South Africa has an extremely diverse climate. The Köppen-Geiger climate classification system is seen as the standard tool for classifying the different climate regions of the world (Peel et al., 2007; Rubel & Kottek, 2010). According to the Köppen-Geiger classification, South Africa has 8 different climatic regions (Figure 1-1), (Table 1-1). The western parts of the country (e.g. Kalahari and Western-Karoo regions) are arid with dry winters that receive very little precipitation annually. The south-western parts of the country (e.g. Cape) are warm-temperate with steppe¹ like precipitation. The south-central parts of the country (eastern-Karoo) are arid and also receive steppe¹ like precipitation. The cold and arid climate of the western parts of South Africa are mainly attributed to the Benguela current that brings dry air and cold water from the southern Atlantic Ocean up the west coast. Due to the warm Agulhas current that brings warm water down from the equatorial regions of the Indian Ocean through the Mozambique Channel to the eastern parts of the country (e.g. KwaZulu-Natal and south coast) are classified as warm temperate climate regions that are fully humid and receive a lot of rainfall. The climate of central South Africa (Highveld) is classified as warm and temperate with dry winters and warm summers. Lastly the northern parts of the country (Limpopo) are classified as arid with steppe¹ like climate and very hot in the summer.

The rainfall regime over South Africa in recent times (since 1970), have been characterised by strong inter-annual rainfall variability (Harrison, 1984; Todd & Washington 1999; Rouault & Richard, 2003). The average rainfall of South Africa exhibits significant variation along an east-west gradient. The east coast and escarpment receives in excess of 1000 mm of rainfall annually, while the west coast only receives about 200 mm annually (Figure 1-2).

¹ Steppe climate: semi-arid region with precipitation below potential evapotranspiration.

Table 1-1: Key to the Köppen-Geiger climate symbols (Peel et al., 2007).

Main climates	Precipitation	Temperature
A: equatorial	W: desert	h: hot arid
B: arid	S: steppe	k: cold arid
C: warm temperate	f: fully humid	a: hot summer
	s: summer dry	b: warm summer
	w: winter dry	

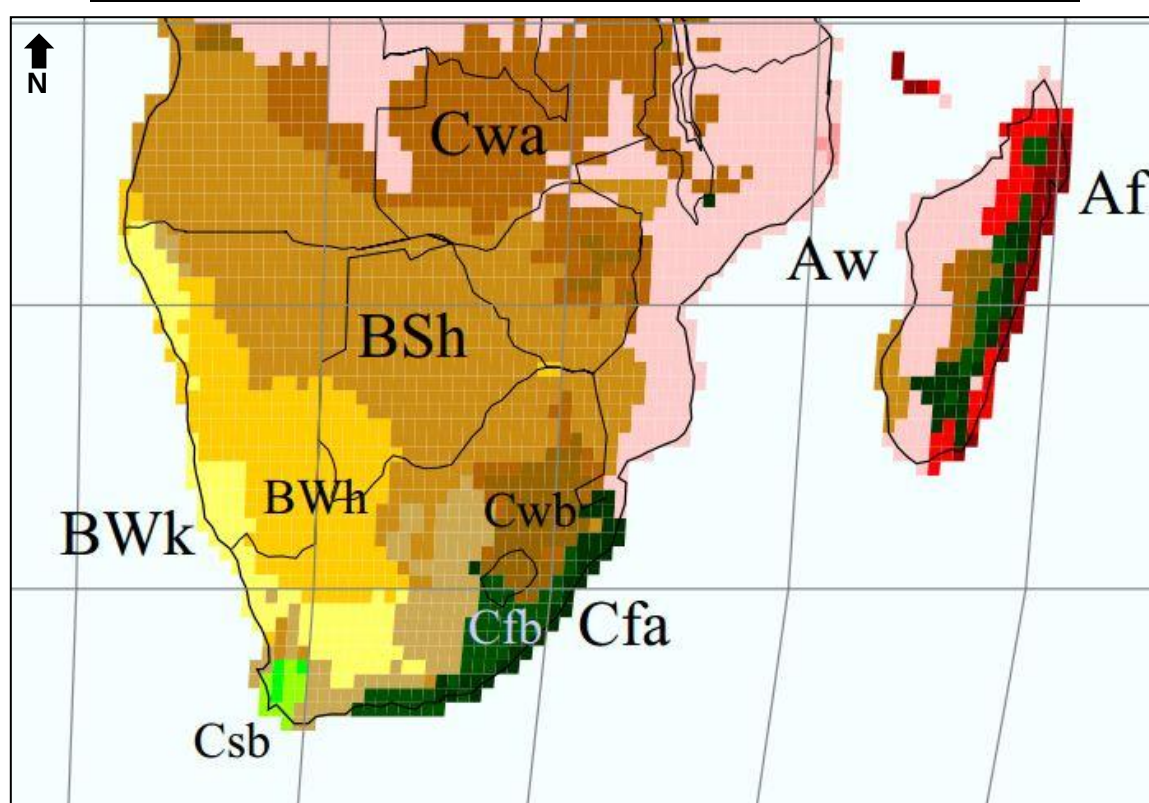


Figure 1-1: Köppen-Geiger climate type map of southern Africa (Kotteck et al., 2006).

The SAWS have identified 93 distinct rainfall districts across the South Africa. Using the basic principles of the Köppen-Geiger climate classification system (Figure 1-1 and Table 1-1), these 93 districts were then divided into 8 homogeneous rainfall regions with the use of a clustering analysis (Rouault & Richard, 2003). Figure 1-3 shows the location of each of the 8 rainfall regions and the 93 rainfall districts. Figure 1-4 shows the mean monthly precipitation of the 8 rainfall regions. The North-Western Cape region (Area 1) receives very little precipitation throughout the year with a maximum of 30 mm in the winter (June). The South-Western Cape (Area 2) also receives the most of its precipitation during the winter but with a much higher maximum of 70 mm. Both Areas 1 and 2 can be classified as winter rainfall regions (Figure 1-1 and Figure 1-3). The

South Coast region (Area 3) receives more or less uniform amounts of precipitation ranging from, 30 mm to 40 mm throughout the year. The Southern Interior (Area 4) receives the most of its annual rainfall during the late summer months with a maximum of 60 mm in March. The Western Interior (Area 5) also receives most of its rainfall during the late summer months but it differs from the Southern Interior because it has slightly lower maximum rainfall of 50 mm in March and the winters are very dry. The Central Interior (Area 6), KwaZulu-Natal (Area 7), and North-Eastern Interior (Area 8) all receive their maximum rainfall in January. KwaZulu-Natal (Area 7) is the wettest region of the three and receives a maximum of 130 mm rainfall in January. The biggest variation of monthly rainfall can be found in the North-Eastern Interior (8), where a 10 mm rainfall deficit can be considered a drought but not necessarily in another area (Area 7).

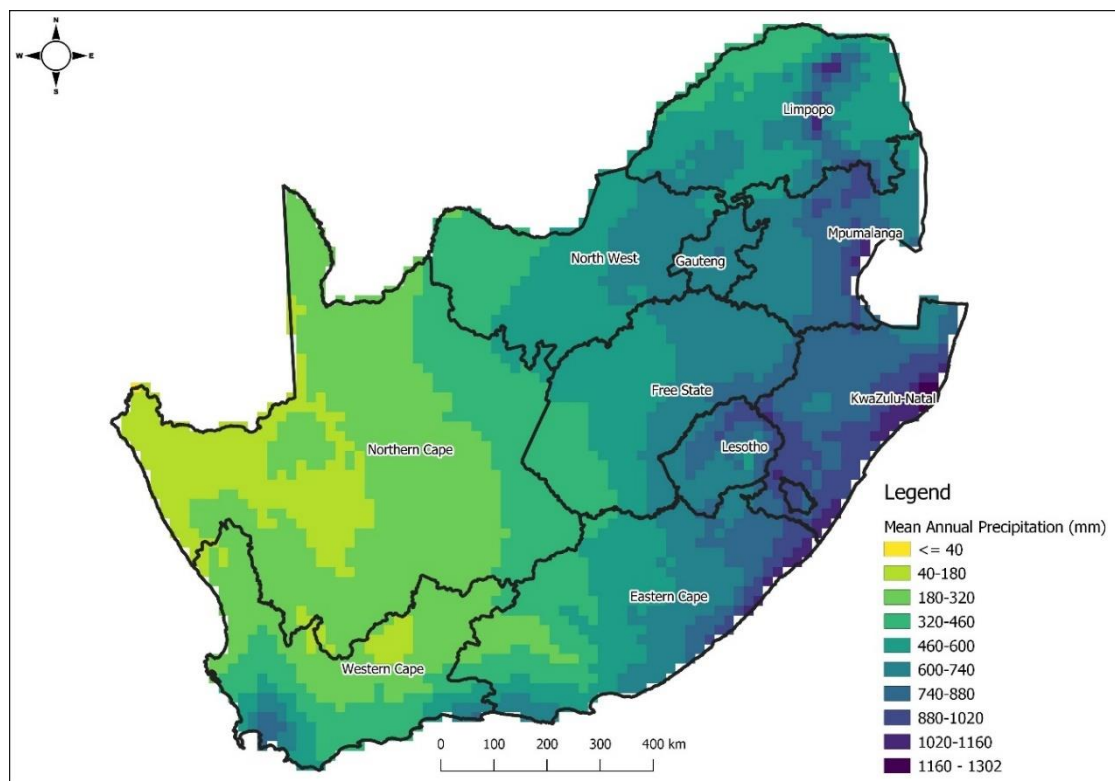


Figure 1-2: The mean annual precipitation of South Africa (Fick & Hijmans, 2017).

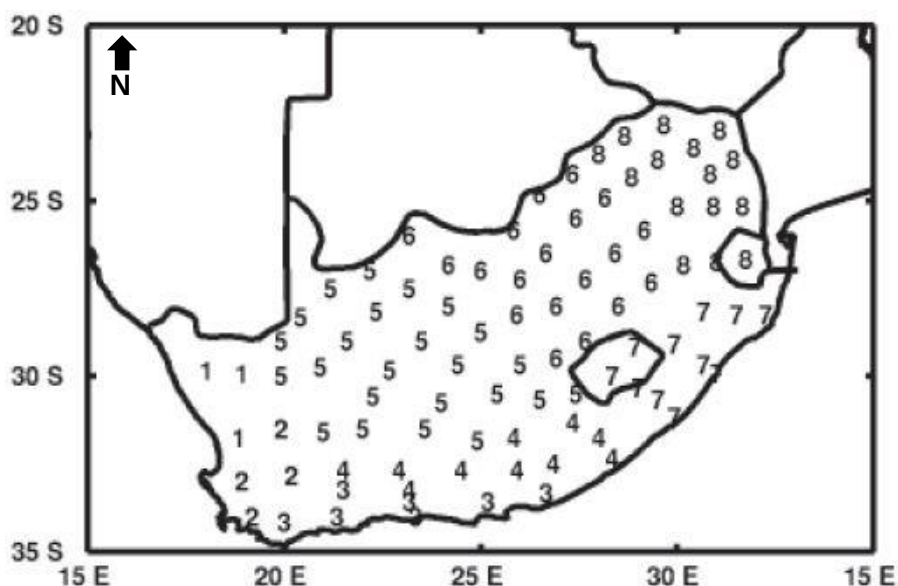


Figure 1-3: The different rainfall districts defined by SAWS. Each number represents a homogenous rainfall region: North-Western Cape (1); South-Western Cape (2); South Coast (3); Southern Interior (4); Western Interior (5); Central Interior (6); KwaZulu-Natal (7); North-Eastern Interior (8) (Rouault & Richard, 2003).

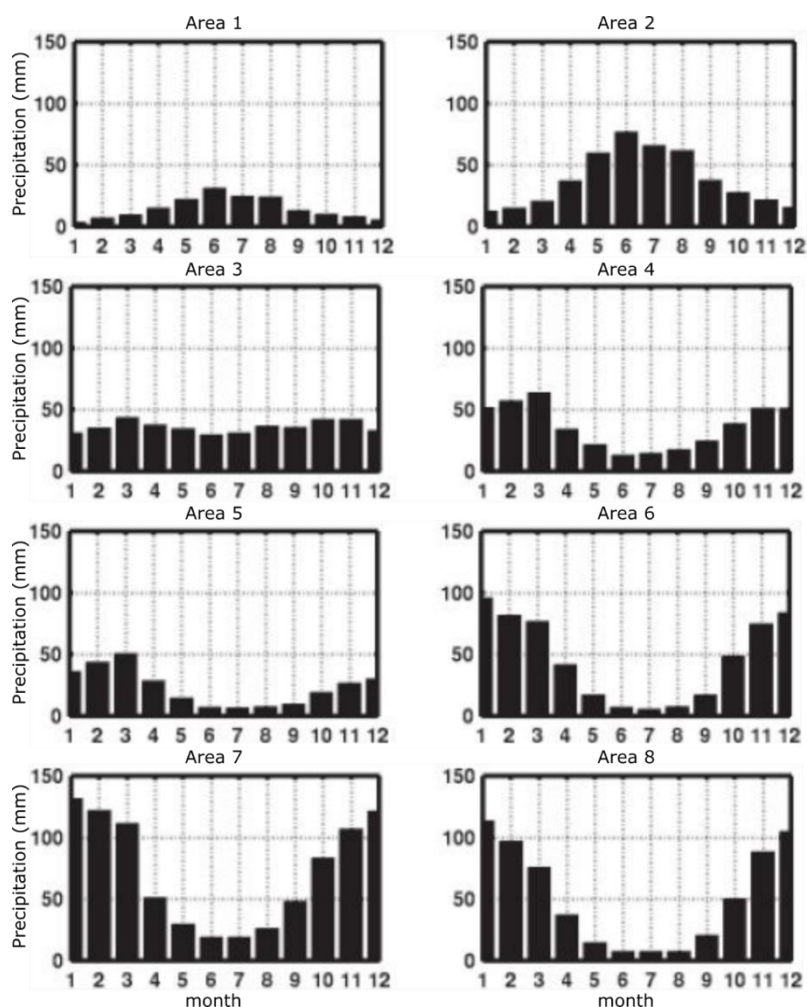


Figure 1-4: Mean monthly precipitation (mm) of South Africa (1921-2001) for the 8 homogeneous rainfall regions as defined by SAWS (Rouault & Richard, 2003).

1.2.2 The spatial and temporal variability of rainfall in South Africa

The variability of rainfall is dependent on various orographic and meteorological factors such as: atmospheric circulation, latitude of occurrence, topography, nearness to centres of large landmasses or water bodies, El Niño-Southern Oscillation² (ENSO) phenomenon, La Niña³, land-atmosphere feedback and sea surface temperatures (SST). Each of these aspects can in turn have an influence on the prevailing atmospheric dynamics and circulation (Sharon, 1972; Levey & Jury, 1996; Nicholson, 2000; Barbe et al, 2002; Pedersen et al., 2010). When looking at all the spatially variable parameters of the climate, precipitation stands out head and shoulders above the rest in terms of spatial variability due to its discontinuity in both space and time. The Global Precipitation Climatology Project that was established in 1986 to develop a more complete understanding of the spatial and temporal patterns of precipitation estimates have concluded that annual global precipitation is about 1050 millimetres per year (Pidwirny, 2006). This however isn't representative of many regions on earth that receive precipitation much less or more than that average. Precipitation tends to decrease nearing the poles and increases in the direction of the subtropical regions. Precipitation around the equatorial regions has the highest annual totals whereas the driest places on earth usually lie near the tropics of Cancer and Capricorn. Furthermore, precipitation tends to become more seasonal as one moves away from the equator due to the shifting dynamics of earth's wind and pressure systems (Sontakke et al, 2009).

The nature of rainfall variability over Africa has fluctuated remarkably in modern times. A study on the nature of rainfall variability of Africa done by Nicholson, (2000), found that there are significant differences in the casual mechanisms driving rainfall variability in southern- and northern- Africa, but a relative synchronicity of rainfall fluctuations exists in the two hemispheres. During January there is predominantly a low-pressure over southern Africa. The Intertropical Convergence Zone (ITCZ) also moves southward during this time, where it can penetrate far into the southern hemisphere. In July/August, this picture is however reversed with a high pressure covering the southern parts of Africa. These prevailing patterns and their seasonality are a direct consequence of the circulation patterns of the southern hemisphere. Rainfall is generally associated with mid-latitude westerlies and the convergence zones. Therefore, the longer a season is dominated by one of these systems in a particular region, the more rain this region will receive annually. Rainfall regimes in the southern hemisphere of Africa can be very complex. Summer rain is predominant, with a January maximum most common.

² El Niño-Southern Oscillation is the warming of the ocean surface to above-average SST in the Pacific Ocean.

³ La Niña is the cooling of the ocean surface to below-average SST in the Pacific Ocean.

There is a marked intra-seasonal and inter-annual variability of the climate over South Africa (Tyson et al., 1975; Harrison, 1984; Levey & Jury, 1996; Kruger, 2006; Ghile & Schulze, 2008; Pohl et al., 2009; MacKellar et al., 2014; Piketh et al., 2014). The circulation of the atmosphere above South Africa is the main driving force behind the variability of weather and climate. Even though circulation patterns of atmospheric pressure, wind and precipitation constantly change, certain basic pressure and wind patterns that underlies them stays constant. Figure 1-5 (a-j) shows the dominant synoptic patterns over South Africa: the continental high Figure 1-5 (a), is a semi-permanent high-pressure system located over the interior of the sub-continent. It is most evident during the winter months where it brings cold, fine and dry weather over the central parts of the country. This type of system can also produce severe heat waves during summer months, often lasting for up to 4 days. The coastal lows Figure 1-5 (b), are usually associated with Berg winds and are the consequence of cyclonic vorticity of air that moves from west to east of the high interior of the plateau and over the escarpment. All coastal lows will have warm offshore airflow in front of it and colder onshore airflow behind it. Easterly waves Figure 1-5 (c) and easterly lows Figure 1-5 (d), form as a result of barotropic disturbances in the tropical easterly flow. The easterly wave Figure 1-5 (c), is associated with strong uplift that can sustain rainfall in the absence of atmospheric instability. Thus, this thermal low occurs in the summer months and is usually associated with convective rainfall over the interior. With easterly lows Figure 1-5 (d), air converges to the east of the low with divergence occurring higher in the troposphere that in the case of the easterly wave. This system can be associated with abundant rainfall over the interior of the country south of the low. It is largely accepted that this type of system differentiates abnormally wet years for dry years over the plateau of South Africa. The westerly wave Figure 1-5 (e), or westerly trough as it is also known, are unlike their barotropic easterly opposites, classified as baroclinic disturbances which propagates in the mid-latitudes as travelling Rossby waves. These systems are the main factors of the winter rainfall that the Western Cape experiences, especially along the coast. If they are particularly deep and strong, these systems usually can bring extreme rainfall and strong winds along the coast. The most intense form of the Westerly trough is called a cut-off low, Figure 1-5 (f). This system starts as a trough in the upper westerlies and then deepens into a closed circulation depression that is cold cored. Passing fronts can develop cut-off low's Figure 1-5 (f), which can bring extreme rainfall and possibly floods in the eastern parts of the country. The southern meridional flow Figure 1-5 (g), originates south of the subcontinent and has a strong zonal pressure gradient between the high in the west and low in the east. This system can bring sustained rainfall to the coastal regions; however, it can cause temperatures to suddenly over South Africa's southern regions. Ridging high pressure's Figure 1-5 (h) or ridging anticyclones as they are otherwise known, bring dry and windy weather during the summer months to southern regions of South Africa, whereas in the east it can bring widespread rainfall due to moist air being advected into the region. During winter these systems

can follow behind cold front and bring cold air to the Western and Eastern cape. The west-coast trough Figure 1-5 (i), brings widespread rainfall to the western parts of South Africa. Lastly cold fronts Figure 1-5 (j) are largely responsible for major changes in surface temperature with abnormally cold air behind the front. These types of systems migrate northwards especially during the winter months when the amplitude of westerly disturbances are at their greatest (Van Heerden & Hurry, 1992; Tyson & Preston-Whyte, 2000).

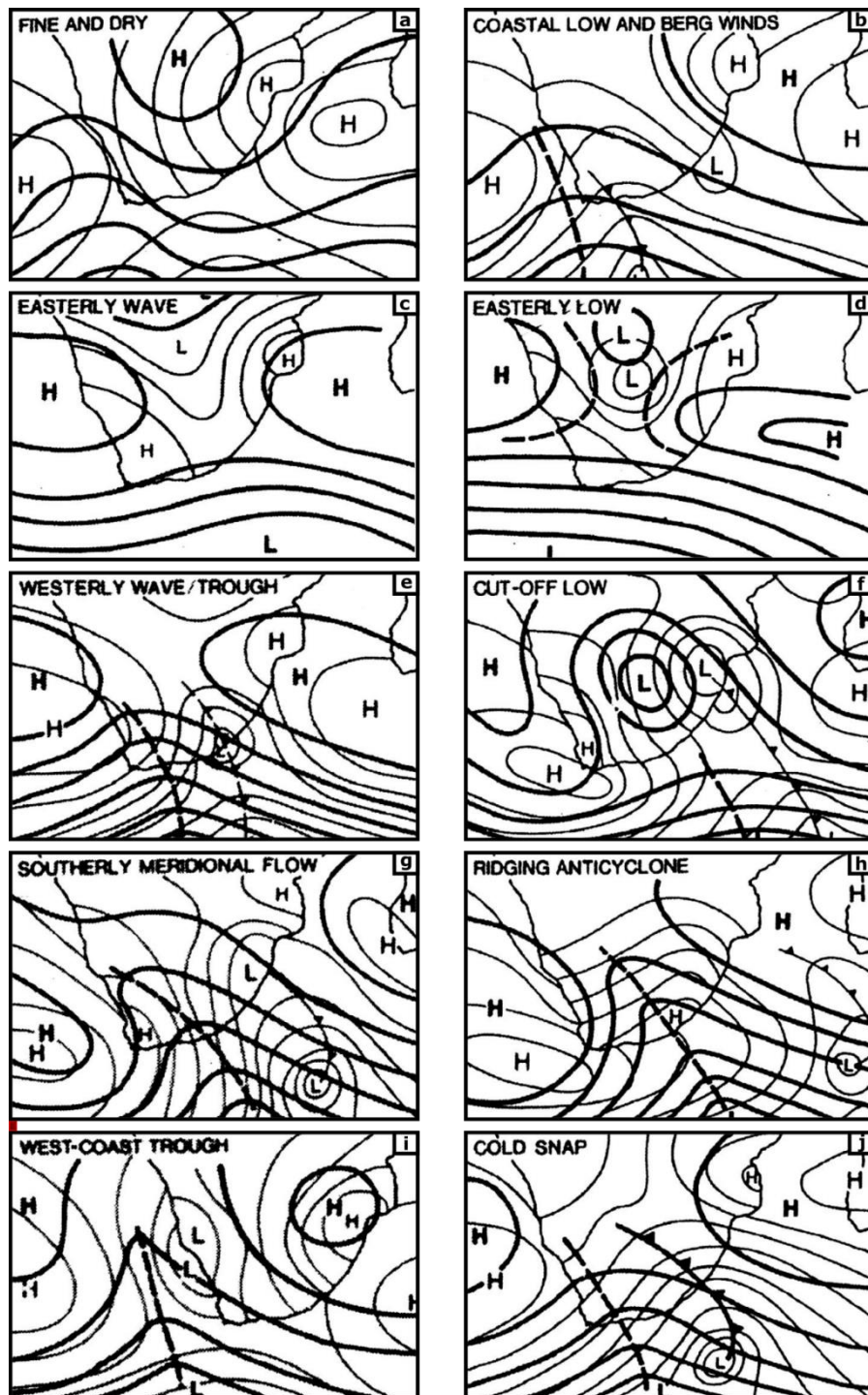


Figure 1-5: The dominant synoptic patterns over South Africa (Tyson & Preston-Whyte, 2000).

The four predominant circulation types which are used in determining transport climatology for the subcontinent are as follows: semi-permanent subtropical continental anticyclones centered over eastern South Africa, transient ridging anticyclones in the westerlies, barotropic semi-stationary easterly waves with trough lines over western interior and traveling disturbances associated with baroclinic westerly waves and the passage of cold fronts. Dynamically disturbed conditions include: passages of vigorous, unstable baroclinic westerly disturbances and lastly, cumulus convection or convergence and uplift in stratiform cloud systems. These disturbances occur 18% of the year and produce 86% of total annual rainfall over central plateau areas of South Africa (Cosijn & Tyson, 1996).

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 widespread and can last for long periods of time. Under tropical rainfall conditions the atmosphere has a stratiform structure that includes high level cirrus clouds which do not bring rain. The Agulhas current produces moisture that moves inland, enhancing storms on the interior. The relationship between this current and the atmosphere greatly affects precipitation (Rouault et al., 2001).

Numerous studies have investigated the variability of rainfall worldwide (e.g. Türkeş, 1996; Singh, 1997; Goovaerts, 2000; Merz et al., 2005; Buytaert et al., 2006; Carrera-Hernández & Gaskin, 2007; Aravena & Luckman, 2009; Türkeş et al., 2009; Villar et al., 2009; Sivakumar, 2013, etc.). These studies have addressed various aspects of rainfall estimation such as: statistics, interpolation, scaling, stream flow hydrographs, rain rate, general circulation models.

Common statistical methods used in assessing rainfall variability include bias (b), root mean square error (rmse), and correlation coefficients (r) (Ali et al., 2005). Pearson's product-moment correlation is most commonly used to investigate the spatial correlation of rainfall (for examples, see Ciach and Krajewski, 2006; Villarini et al., 2008; Mandapaka et al., 2010; Pedersen et al., 2010; Peleg et al., 2013).

Singh (1997) found that the intensity and distribution of rainfall over a catchment can change with intervals of a minute or less and that the temporal variability of rainfall produces much greater peak discharge than constant rainfall.

Knowing the spatiotemporal variability of rainfall with daily (or better) resolution is essential in the investigation of the climatology of extreme events, or in the evaluation of numerical weather prediction models. Rainfall maps for various applications have to be available as close to real-time as possible. Rain gauges form the backbone of these maps since the reliability of remote sensing data (radar & satellite) is not high enough (Ahrens, 2005).

Most studies done on the spatial variability of rainfall has been focused on domains of less than 40km in linear extent, through ground based and rain gauge networks. The correlation distances between rain gauges, which are dependent on the storm and gauge network characteristics, have been commonly determined with the Pearson's three parameter exponential function for estimating inter-gauge correlations. Highly variable storm events are characterized by shorter correlation distances than the more moderate and widespread storms. In an ideal world the inter-gauge distances will be as close as possible, but logistical challenges usually dominate the selection of a gauge site. Furthermore, one will find that the correlation distances are also longer where there are long integration periods between gauge and radar (Tokay et al., 2014).

1.2.3 Measuring rainfall on the ground

The measurement of rainfall has always been of great interest to the scientific community. Ground based rainfall measurements are used for a variety of hydrological purposes ranging from, information on agricultural water supplies to flash flood forecasting. By measuring and observing rainfall, patterns can be recognised, and these patterns can be used to predict or forecast rainfall. Rainfall abnormalities that are a direct consequence of climatic variation, have received considerable attention in the hydrological field of study over the past few decades. The atmospheric circulation on both regional and global scales and the drivers of rainfall variability have greatly intensified the interest in rainfall measurements on all scales (Atlas, 1990). Thus, the importance of measuring rainfall cannot be overstated.

Traditionally, rainfall is measured with rain gauges that measure the true rainfall that falls over a small area of a few squared centimetres. Rain gauges make direct measurements of rainfall over time and therefore are considered to make rainfall measurements with a high degree of accuracy. Despite the known uncertainties to rain gauge measurements many consider rain gauge data to be the ground truth for the real rainfall reaching the ground (Duchon and Essenberg, 2001; Martens et al., 2013). However, rain gauge networks are usually too sparse to capture the spatial variability of rainfall (Villarini et al., 2008). Remote sensing of rainfall offers an alternative approach to characterise the spatial variability of rainfall over large areas. One method of remote sensing is the use of weather radar for rainfall measurements. Radar has the ability to sample the spatio-temporal properties of rainfall at a high resolution. Other popular rainfall measurement tools are disdrometers as well as active and passive sensors on-board space borne satellites. A rain gauge measures rainfall by collecting it at ground level over a circular area with a diameter of about 20cm², a distrometer's sample area is roughly 50cm² and radar scans the atmosphere 360° at various elevations and azimuths which gives a projected sampling area of roughly 1 km².

Thus, one can assume that the observation scales differ with a ratio of approximately 10^7 between rain gauge and radar (Kassim and Kottegoda, 1991; Gires et al., 2014).

1.2.3.1 Rain gauges

Rain gauges are not only used to measure how much rain has fallen over a certain area, but to also provide information on rain rates and to validate and calibrate other rainfall measuring technologies such as weather radars and satellites. Thus, it is extremely important that the data obtained from a rain gauge is accurate and reliable (Upton & Rahimi, 2003). Generally, there are four types of rain gauges that are being used to measure rainfall around the world: the standard gauge, the tipping bucket gauge, the weighing gauge and the disdrometer (WMO, 2008). The differences between these gauges are the price, mechanical complexity, temporal resolution and the magnitude of measurement error made by each of these instruments.

According to the World Meteorological Organization (WMO), 2008; the most important requirements for a rain gauge are that: The edge of the collector should be sharp and fall away vertically on the inside, and be reduced to a steep sloping edge on the outside. The orifice dimensions should be known to the nearest 0.5 per cent and it should be constructed in such a way that the dimensions stay constant throughout the lifespan of the gauge while. The design of the collector should prevent rain from splashing in- or out during most rain intensities. This requires the vertical wall of the gauge to be sufficiently deep and the slope of the funnel to be sufficiently steep (at least 45 per cent as shown in Figure 1-6). The gauge should be designed to minimize wetting errors. The funnel should have a narrow inlet and be sufficiently protected from direct sunlight as to protect rain from being lost due to evaporation. If a gauge is located in a place where frequent recordings are not practical, the gauge should have a similar design to the daily gauges, but with increased storage capacity and stronger construction. The measurement cylinder should be made of clear glass or plastic that can handle extreme thermal expansion. The diameter of the measuring cylinder should be no less than 33 % of the diameter of the rim of the gauge collector (A smaller diameter results in higher precision). The cylinder should be finely engraved with graduation markings at 0.2mm intervals. Also, the line corresponding to 0.1 mm should be clearly indicated. The inside diameter of the measuring cylinder should taper off at the base, to increase the precision of measuring small amounts of rain.

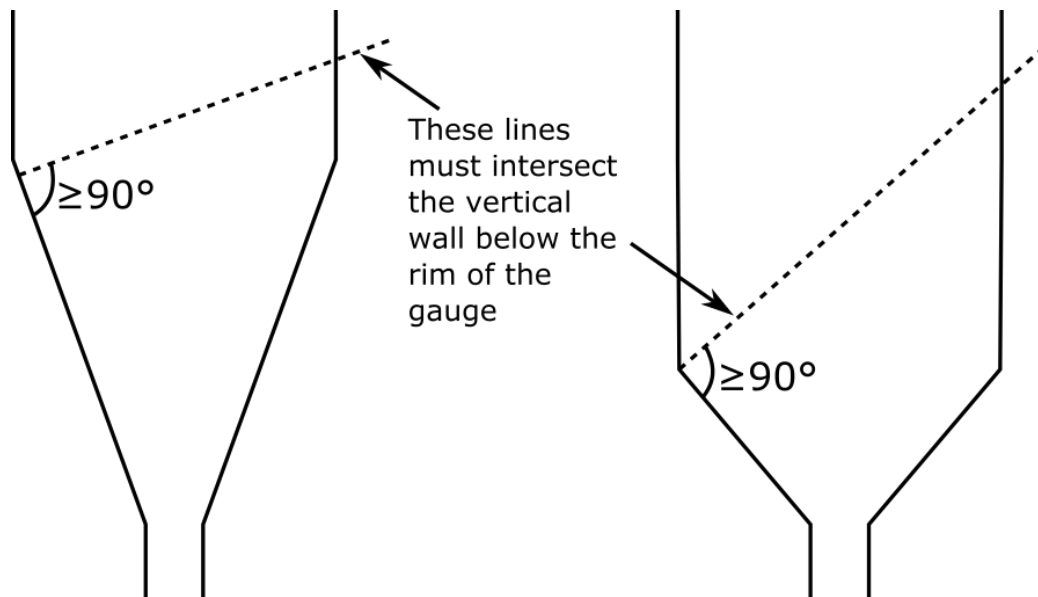


Figure 1-6: Suitable design for rain gauge collector, where the angle at which funnel and vertical rim of the gauge, intersects is very important (WMO, 2008).

Standard/Ordinary rain gauges

The standard rain gauge is a very popular rainfall measuring instrument and consists of a collector that is placed above a funnel leading into a measuring cylinder where accumulated rain water is stored between observation times. These gauges are the cheapest and simplest type of gauge and are common in urban house gardens and on farms. According to Strangeways (2010) there are over 50 different types of standard rain gauges in use worldwide. Thus, standard rain gauge comes in various shapes and sizes as shown in Figure 1-7 (Sevruk and Nespor, 1994).

The standard rain gauge is however a non-recording gauge which is prone to making various types of errors in its rainfall measurements. Standard rain gauges are unsuitable for use during high wind speeds. Air flow around the gauge tends to carry rain over the head of the orifice, causing wind speed-dependant undercatch of rain (Yang et al., 1998). This is a result of the structure of the standard rain gauge being an obstacle that creates updrafts on the upwind side of the gauge (Folland, 1988; Hasse et al., 1998).

Standard rain gauges are based on the principle of collecting rain water in a container which has to be recorded manually on a daily basis. When this is not done, water accumulates in the container for very long periods of time and results in some water being lost through evaporation and wetting when the container is emptied (Rubel and Hantel, 1999; Sevruk et al. 2009). Therefore, if the measurement that is made by this gauge is not recorded immediately after each rainfall event, the actual amount of rain that has fallen over a certain period of time is not recorded accurately. In most cases the gauge measurement is not taken directly after each rain event, thus water is almost certainly lost causing an error in the measurement. Another drawback of the

standard rain gauge is the fact that it cannot provide information on the rain rate, which makes them unsuitable for applications such as flash flood predictions and hydrological modelling.

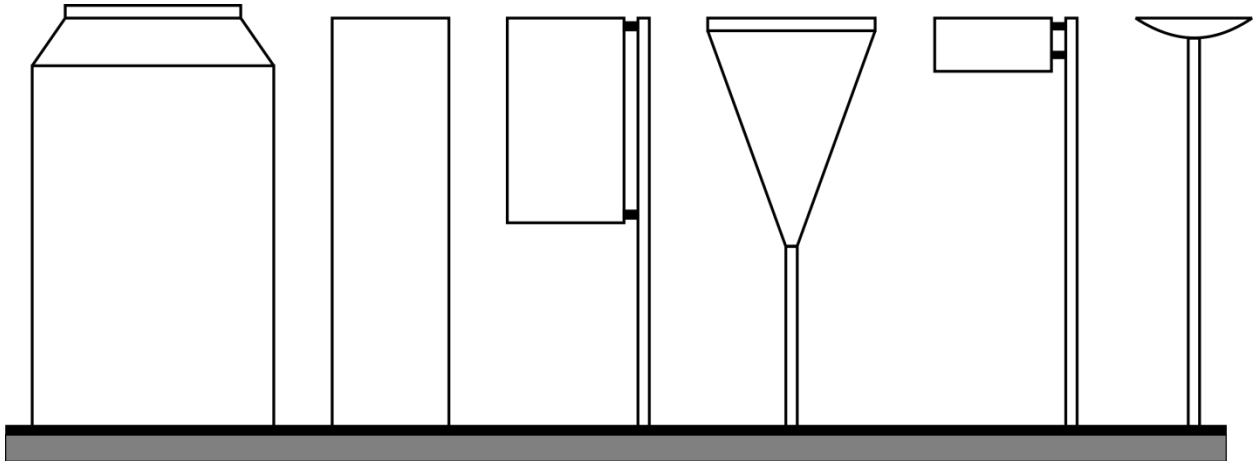


Figure 1-7: A side view of the different shapes and sizes of the standard rain gauge (Sevruk and Nespor, 1994).

Weighing rain gauges

The weighing rain gauge operates on the principle of weighing the container, together with rainwater that has been collected therein on a continuous basis, using a spring mechanism or with a system of balancing weights (Figure 1-8)(Nystuen et al., 1996; Nystuen, 1998; Nystuen, 1999 WMO, 2008). The weighing rain gauge is commonly used for measuring snow, hail, and mixtures of snow and rain, since the solid precipitation does not have to melt before a measurement can be recorded.

There are various types of mechanical errors associated with weighing rain gauges. These errors are described by Nayak et al, (2008) as either high or low amplitude noise. High amplitude noise can be caused by out of range data values, the bucket decanting, recharge and intermittent noise on the bucket. Data values can fall out of range when the instrument or data logger is not working, causing discontinuities to arise in the data. While the gauge is being serviced the bucket is decanted and then recharged with oil and antifreeze. This process can cause large negative changes in the weight of the bucket but can also be positive changes when it is being recharged with too much oil or antifreeze. These gauges are also occasionally subject to large instantaneous changes from intermittent electronic noise. Low amplitude noise can either be periodic due to temperature fluctuations affecting the electronics, or episodic, due to wind induced vibrations on the gauge.

The drawback of this type of gauge is that there is normally no provision made for emptying the accumulated rain water from the gauge, thus it has to be done manually which can be very labour intensive which in turn complicates the maintenance of these gauges, especially when gauges are located in remote areas.

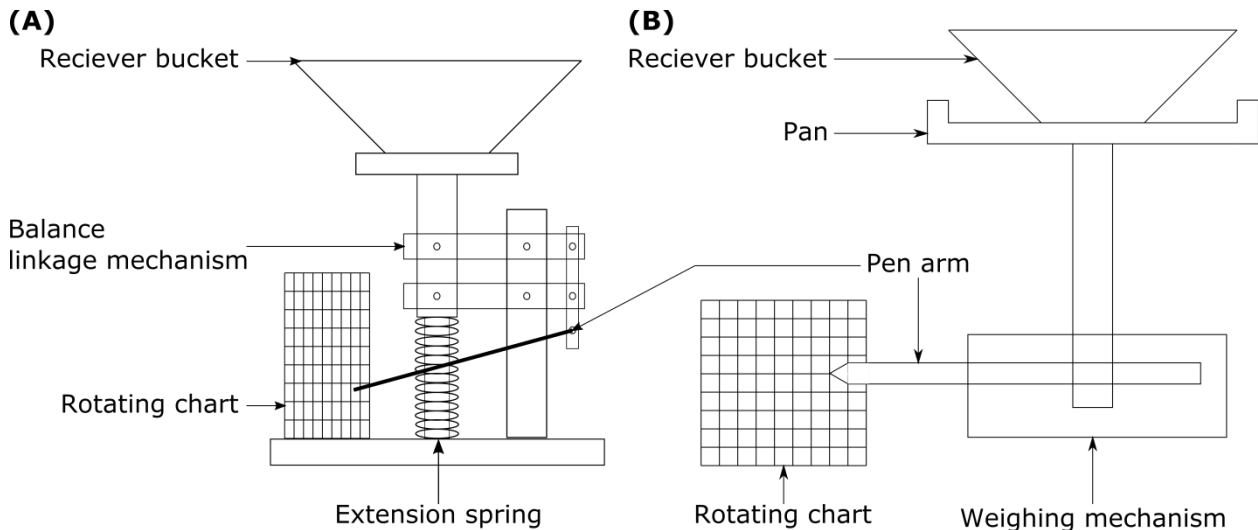


Figure 1-8: The different types of weighing rain gauges. (A) Uses a spring mechanism and (B) uses a system of balancing weights. Both of these weighing gauges' record rainfall measurements on a rotating chart.

Disdrometer

The distribution of rain drop sizes has been of interest to scientists for a very long time. A disdrometer can measure the size and velocity of rain particles (Löffler-Mang & Joss, 2000). Radar returns are dependent on drop size distribution and thus the use of optical rain gauges has become very important for radar and satellite calibration and validation purposes. The advancement of technology has made the use of new rainfall recording techniques such as the disdrometer, not only for determining drop size distribution, but also for the use as a simple rain gauge (Grossklaus et al., 1998). There are generally three types of ground based disdrometers: the optical disdrometer/rain gauge, the impact disdrometer, and the Doppler radar disdrometer (Tokay et al., 2002). These disdrometers are very popular due to their ability to make very accurate measurements of individual particles. These instruments are therefore considered to be the most accurate of all ground based rainfall measuring methods (Tokay et al., 2001). The characteristics and operating principles of the optical and impact disdrometer will be discussed in the following section.

The optical disdrometer/rain gauge consists of two housing units which accommodate the receiver and transmitter (Figure 1-9). The horizontal laser beam (Figure 1-10) that is projected between

the two housing units has a sampling size range between 50-54 cm² and can provide drop size distribution (DSD) measurements as well as information on the quantities derived from DSD such as rain rate R and radar reflectivity Z (Tokay et al., 2001; Kruger & Krajewski, 2002; Jaffrain & Berne, 2011). Figure 1-10 (a) schematically shows what happens when two particles of different sizes cross the laser beam. The attenuation of received voltage that is created by particles as they cross the laser beam is used to estimate the size of each drop and the time the particle takes to leave the beam is used to estimate the velocity of each drop (Figure 1-10: b, c).

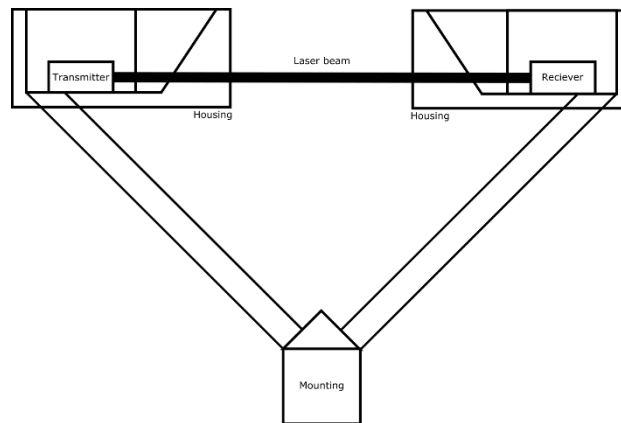


Figure 1-9: A cross section of the optical rain gauge or disdrometer as it is also commonly called.

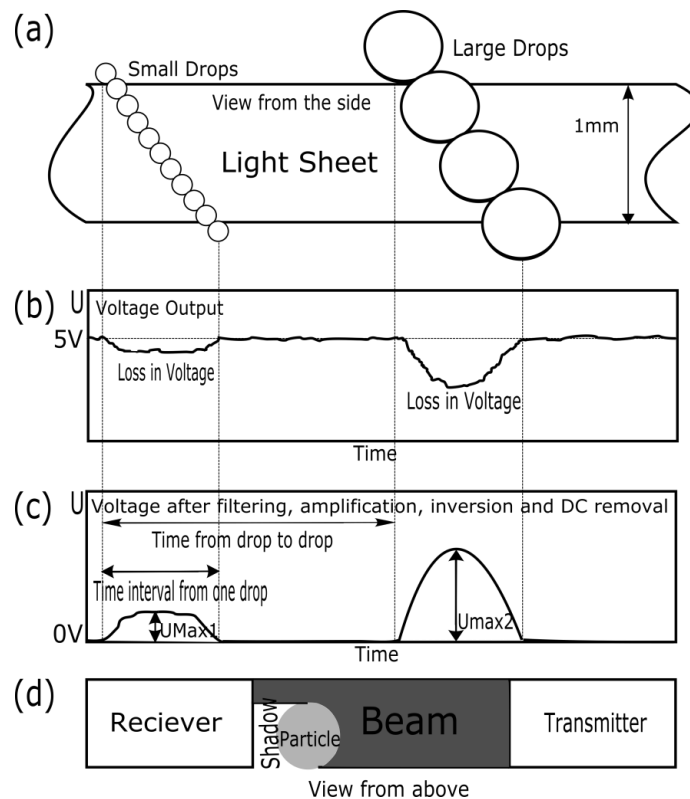


Figure 1-10: The process of measuring rainfall with an optical rain gauge. (a) Small and large particles as they fall through the beam, (b) attenuation from the particle as it moves through the laser beam, and (c) inverted and amplified signal after thresholding for

measuring purposes (d) the shadow that a particle creates as it falls through the laser beam.

The impact disdrometer that was originally developed by Joss and Waldvogel (here after JW) is the most commonly used electromechanical disdrometer (Löffler-Mang & Joss, 2000; Williams et al., 2000; Tokay et al., 2002). The JW disdrometer, which has been on the commercial market for over 30 years, was originally designed to calculate radar Z (Tokay et al., 2001). However, with the advancement of technology this instrument has become the standard device for measuring DSD on the ground (Caracciolo et al., 2006). The JW disdrometer can measure drop size with 5% accuracy and it can estimate the diameter of drops by sensing the voltage induced through the downward displacement of the 50 cm² sampling area.

Some of the drawbacks of the JW disdrometer are that: immediately after a rain drop has impacted the transducer, there is a dead-time where no rain drops are detected due to the recovery time of the instrument, it underestimates the number of small rain drops during heavy rain, it cannot sort rain drops into a size when they are larger than 5.5 mm in diameter, and its calibration assumes that each rain drop is falling at a terminal velocity (Tokay et al., 2002).

Tipping bucket rain gauge

(TBRs) have been extensively used for collecting rainfall data since their inception in the 1600s. TBRs are widely used by the South African Weather Service (SAWS) and many other organisations and weather services, with an estimated 20 000 TBRs being used worldwide. The TBR's popularity is mainly because of its durability, simplicity and digital form of data output (Maksimović et al., 1991; Upton and Rahimi, 2003; Vasvári, 2005; Fiser & Wilfert, 2009). Other advantages of this type of gauge are that they can be used in remote areas unlike standard and weighing gauges which need to be continuously emptied and recorded. The TBR can be connected to various recording and monitoring devices, and are relatively inexpensive.

The TBR works on the following basic principles. Rain water is collected in the funnel, where it goes through a filter into the syphon. The syphon ensures that the flow of water into the bucket assembly is constant during all rain rates. When the syphon is full, all the water from the syphon is drained into one of two buckets that are balanced on a horizontal axis. These buckets commonly have a predetermined capacity of 0.2 mm and once this amount of rain has been collected in one of the buckets, it will tip and drain that bucket, causing the other bucket to move into place to start collecting rainwater. Each tip causes a magnet to create an electronic signal to be sent to a data logger (Figure 1-11). On the data logger the time of each tip is then recorded. Knowing the time and volume of each tip makes it possible to calculate the incremental amount of rainfall over variable or fixed intervals of time (Humphrey et al, 1997; Thyregod et al., 1999, Wang et al., 2008).

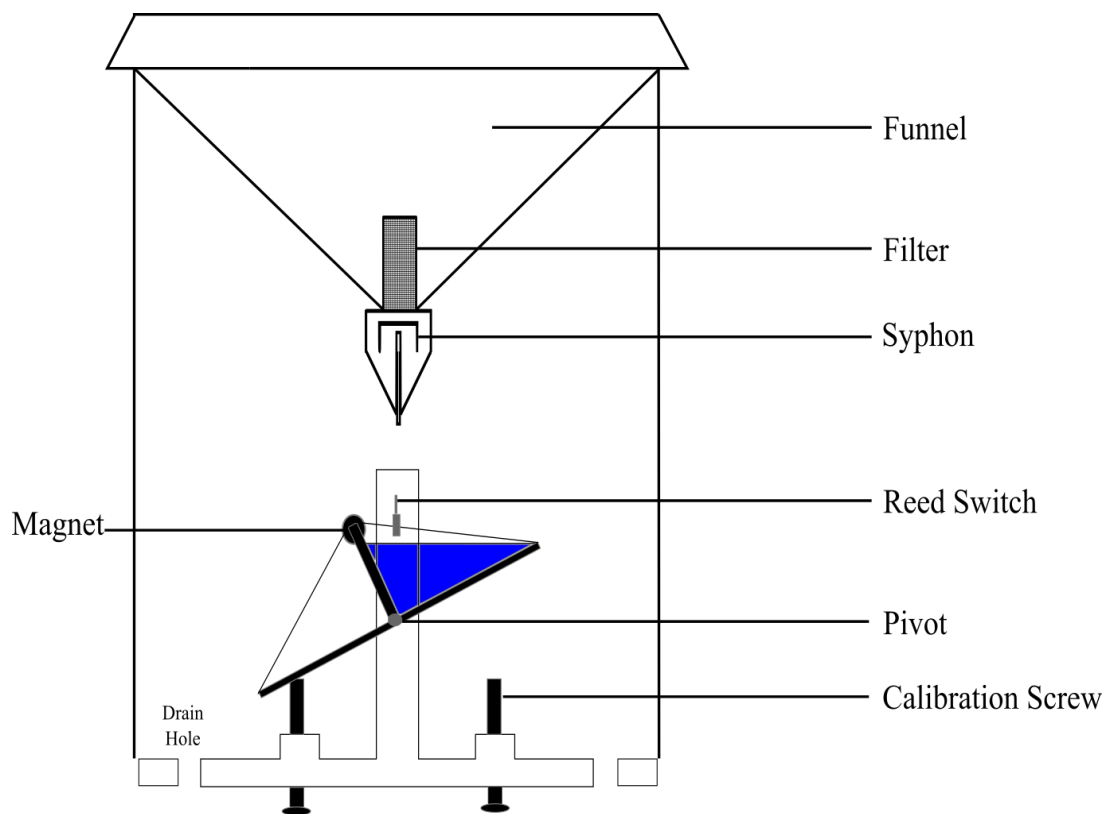


Figure 1-11: A schematic of the tipping bucket rain gauge mechanism and its essential parts.

According to Upton & Rahimi, 2003, the most common problems that TBRs experience when attempting to measure rainfall are: *High rain rates*: The TBR can make significant measurement errors during high rain rates. This happens because the tipping action of the gauge's buckets are not instantaneous as the water streams in through the funnel and then it can happen that water is lost between the consecutive tips of the buckets, resulting in under-catch due to the high rain rate (Molini et al., 2005; Duchon & Biddle, 2010). *Evaporation and Wetting*: A common problem with all rain gauges is losses of water due to wetting and evaporation refers to the water that is left on the sides of the funnel, thus not going into the collection chamber and then the water evaporates (Humphrey et al., 1997; Anders et al, 2006). *Blockages*: Partially blocked gauges can lead to errors in rain rate estimates. Blocked gauges can cause gaps in the data record and thus skew the estimates of the total rainfall of a period of time. *Wind effects, positioning and shelter*. Gauges that are placed next to each other but at different heights can measure different rainfall amounts due to the variation in height of the local wind field. Wind-induced losses of rain can be as much as 15% during light rain as a consequence of the distortion which the gauge creates in the wind field above the gauge orifice (Sevruk, 1996; Ciach, 2003).

1.2.4 Rain gauge networks

Most locations around the world lack sufficient rainfall monitoring networks which are an essential requirement for most hydrological, climatological and meteorological applications. The distribution of rain gauge networks is in many cases biased toward locations where there is already sufficient infrastructure in place. Rain gauge networks are usually designed so that they are located at lower elevations, near natural resources, along main transport routes for accessibility and maintainability, secure, and near electricity and communication networks (Hong et al., 2007; Cheng et al., 2008).

The inter-gauge distances of some operational rain gauge networks used for radar calibration/validation and for hydrological modelling are often more than 20 to 30 km apart. At such distances it is difficult for a rain gauge network to provide adequate information on the small-scale, spatial structure of rainfall (Ciach and Krajewski, 2006; Pedersent et al., 2010). The definition of network density varies from one source to another, since small scale density is defined by the distances between the gauges of a network which can range from 0.1 km to more than 10 km.

There are already various experimental rain gauge networks around the world, some of which are relatively dense, e.g. the EVAC PicoNet in Oklahoma, USA, which consists of 25 gauges that are spaced 0.6 km apart over an area of 9 km² (Ciach and Krajewski, 2006). Networks with such great density are however quite rare since a lot of gauges, require frequent maintenance and calibration as well as data quality control in order to operate them, all of which can be expensive and time consuming. In Thailand a network of 326 rainfall recording stations is deployed over the 38 000 km² Yom river basin (Putthividhya and Tanaka, 2012). To put it in perspective, if the Yom river basin had the same density as the EVAC PicoNet network, there will have to be 105 555 gauges deployed over the Yom river basin, which had only 326 gauges at the time that Putthividhya and Tanaka, 2012's article was published. This is significant difference in inter-gauge densities between these two networks. It is however important to note that rainfall monitoring networks are set up for different operational functionalities over the world. The EVAC PicoNet network, might be setup purely for high resolution spatiotemporal scientific research purposes, whereas the Yom river basin network might be used for long-term climatological studies that doesn't require such high network densities. The national rain gauge network of South Africa is in decline and is fast becoming too sparse to meet existing and anticipated management requirements (Deyzel et al., 2004; Kroese, 2004). The first experimental high density rain gauge network in South Africa was situated in the Liebenbergsvlei catchment located near Bethlehem in the Free State. The rain gauge network in the Liebenbergsvlei catchments was a dense network which consisted of up to 45 gauges that are spread out over the 4694 km² catchment area

(Mittermaier and Terblanche, 2000; Frezghi and Smithers, 2008; Vischel et al., 2008). However, this network has also been in decline in recent years

The WMO, 1994, 2008; has laid down certain criterion regarding the minimum density of rain gauge networks which is to be followed for different types of geographical locations as given in (Table 1-2).

Table 1-2: Recommended minimum rain gauge densities (km² per gauge).

Physiographic unit	Rain gauge type	
	Non-recording	Recording
Interior plains	575	5750
Hilly/undulating	575	5750
Mountainous	250	2500
Coastal	900	9000
Urban areas	-	10-20
Arid	10 000	100 000

Another consideration to take into account is that, for the adequate sampling of convective-type rainfall, nearly twice as many rain gauges are required when compared to amount needed to sample stratiform rainfall. This is because localised and high intensity rainfall is usually associated with convective events, requiring more gauges to resolve the spatial and temporal variation of rain rate and amount (Peppler, 1991; Westcott, 2013).

1.2.4.1 The location of rain gauges

Ideally a rain gauge should be placed at a site where it would represent the rain falling on the surrounding area. However, this can be difficult to attain in practise due to the effects of wind. Careful considerations therefore have to be taken when choosing a site to place a rain gauge. Wind can directly affect the gauge by causing rain to drift over the inlet, thus reducing the amount of water collected. Gauges should not be placed close to buildings or trees (Sevruk, 1996). These obstacles can cause disturbances in the local wind field, which can lead the gauge to severely over- or under recording of rain falling to the ground. This effect can be reduced or eliminated by choosing a site where the wind speed at gauge level will be as small as possible. According to WMO (2008), the best practise is to place a gauge on a flat and open area where there are no obstructions within a 30° angle around the top of the gauge (see Figure 1-12).

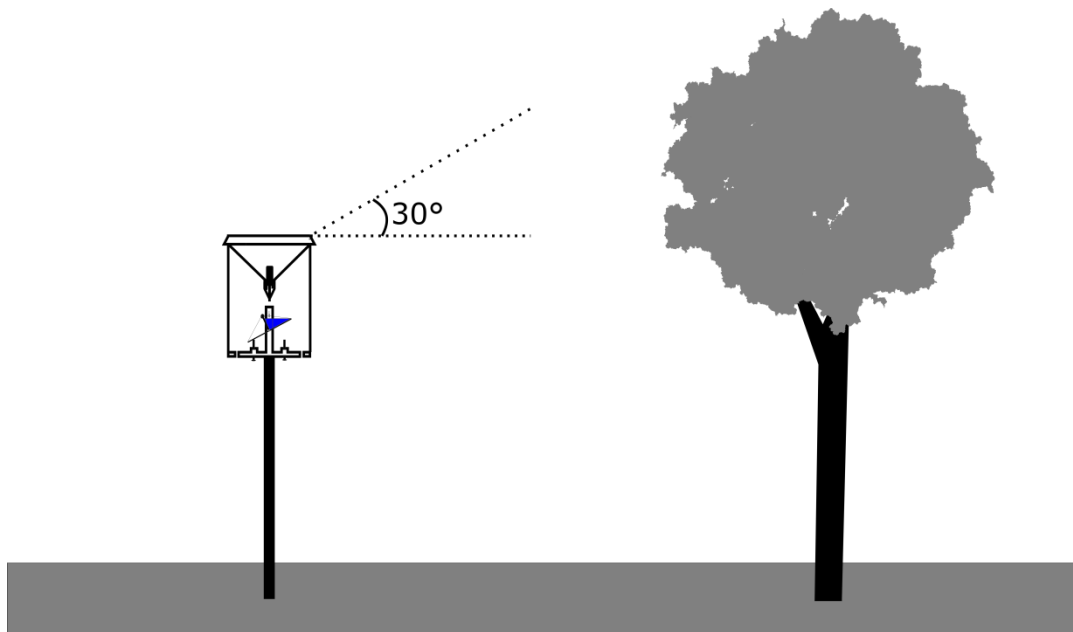


Figure 1-12: The ideal placement of rain gauges in accordance to WMO, 2008 recommendations.

Rain gauges should always be exposed so that the inlet is level to the ground. Sites on a slope and with objects that can produce significant wind disturbances should be avoided. Hard surfaces such as concrete should also be avoided when a rain gauge site is chosen, as these surfaces may cause excessive splashing. Ideally the ground surrounding a gauge should either be short grass or gravel.

1.2.5 Data quality control of tipping bucket rain gauge estimates

Rain gauges do not only provide measurements on rainfall depth, but they also provide information on rain rates. Furthermore, rain gauge measurements are used for the calibration of other weather observation instruments such as radar and satellites (Mittermaier and Terblanche, 2000 and Rouault et al., 2001).

Even though rain gauges give very accurate rainfall estimates, the data derived from them can sometimes be corrupted with errors that are the result of environmental factors influencing the gauge's recordings (Hill, 2013). Some of these factors include high rain rates causing high frequency bucket tips, strong wind gusts causing false tips, clogs and/or poor gauge maintenance and human induced errors. There can also be other technical factors influencing gauge readings, such as instrument malfunction, data transmission errors and format changes (Parzybok et al., 2013; Qi and Zang, 2013). Thus, it is of great importance to do quality control on rain gauge data as it is extremely important that the information obtained from a rain gauge network gives an

accurate representation of the rainfall that it received and that the gauge taking the measurements are reliable and not prone to errors.

Due to the high spatial and temporal variability of rainfall data, most quality control measures employed in rain gauge network simply impose a threshold for which to accept or reject unusually high or low outlier values (González-rouco et al., 2001 and Parzybok et al, 2013).

Rain gauge networks often span over large areas with great distances between each gauge. With conventional/ordinary rain gauges which need to be measured manually, this can be a problem. Losses of recorded rainfall due to evaporation can commonly occur with ordinary rain gauges due to the fact that a data collector have to physically go out to the gauge and check how much rain have been recorded. Due to the sometimes long periods between these checks, evaporation losses occur and long inter-gauge distances makes it difficult for an attendant to make regular visits to each gauge. Another problem with ordinary gauges is that they can mask the extent of wind-induced catching errors due to their rough data resolution. Therefore, it is necessary to make a shift from using manual gauges to automatically recording gauges, especially for use in large rain gauge networks.

The advantages of automatic rain gauges are that they eliminate the need for an attendant to go out and take measurements at each gauge. Therefore, gauges can be installed in remote places that are rarely accessed. It also eliminates the possibility of human error while recordings are taken.

Automatic rain gauges enable the optimisation of the workforce maintaining a network as well as the quality of the data obtained from a network of rain gauges. Thus, a critical step in the optimisation of a rain gauge network is to optimise the quality of data that is recorded by the network. Steiner et al (1999) found that by using all the rain gauge data they had to their disposal, instead of only using good data, there was a 25% underestimation in radar rainfall estimates' that were calibrated using rain gauge data.

1.2.6 Optimal rain gauge network design

The accuracy of point rainfall estimates is directly related to the number and spatial distribution of rain gauges in a network. It is essential that the density and distribution of rain gauges in a network sufficiently reflects the spatial and temporal variation of rainfall in a study area (Shaghaghian & Abedini, 2013). For many applications in hydrology and meteorology, temporal and spatial resolutions of rainfall equivalent to 10 s and 100 m, respectively, are desirable, and if possible, from a multitude of sampling locations (Stow et al., 1998).

The design of a rain gauge network is affected by various factors, such as the functional objective of the network (e.g., water resource management, flash flood forecasting, precision farming), the rainfall variables under consideration (e.g., rain rate, rainfall depth, rainfall distribution and DSD), the spatial scale required (e.g., catchment, regional, national or global), the temporal scale required (e.g., minute, hourly, daily, monthly or annually), the topographic setting (e.g., interior plains, hilly/undulating-, mountainous-, coastal-, or arid- area), precipitation type (e.g., convective, stratiform, and orographic), the objective function used for optimisation of the network (e.g., variance-based, entropy-based, fractal-based or distance based techniques), and the optimisation algorithms used for minimising or maximising current networks (e.g., exhaustive search, generic, simulated annealing, etc.). Factors such as the spatial scale, topography and precipitation type will be dictated by the study area itself, because the earth is non-homogenous, and topography and precipitation can be highly variable from one place to the next. There is a significant link between spatial variability and sampling interval. This refers to rainfall attributes becoming less variable as the sampling interval increases and thus results in lower rain gauge density requirements for measuring rainfall (Cheng et al., 2008; Shaghaghian & Abedini, 2013).

In many cases the density of rain gauge networks, in most catchments, is not up to the minimum standards set by the WMO, 2008. The design of most rain gauge networks therefore warrants further evaluation and augmentation where necessary.

High density rain gauge networks are quite rare since they require multiple gauges, lots of maintenance, calibration and data quality control- all of which are very expensive. There have been many publications on the optimal selection of rain gauges which takes into account the density and distribution of rain gauges in a network in order to acquire greater measurement accuracy of the spatial variability of rainfall with minimum costs. These approaches generally apply statistical theory for rain gauge network design. Awadallah, 2012; Wei et al., 2014 and Chen et al., 2007 used a methodology based on the sequential use of kriging and entropy to determine the optimal number and spatial distribution of potential rain gauges in catchments. Kassim & Kottegoda 1991 Putthividhya & Tanaka, 2012 and Sivapragasam et al., 2012 used geostatistics and probabilistic techniques such as the Minimization of Mean Shortest Distance method, inverse square distance method, Genetic Programming and Ordinary Kriging to assess the optimal localisation of new rain gauges in an existing rain gauge network. Cheng et al., 2008 and Pardo-Igúzquiza, 1998 used the popular geostatistic method of variance reduction. This method entails a methodological search for the appropriate number of rain gauges and their spatial distribution within a catchment. This reduces the variance of estimation errors for rainfall events that is commonly made by many rain gauge networks.

Mathematical interpolation techniques are traditionally used to estimate rainfall at un-gauged sites. The merging of rainfall fields derived from radar and rain gauges are considered to be adequate for estimating the true rainfall field (Frezghi & Smithers, 2008).

One method of estimating values in the unknown field between rain gauges is statistical interpolation. Optimum interpolation between rain gauges can be implemented by kriging. Kriging makes the assumption that there is a local structure in the sampling domain and the accuracy of estimations is dependent on how this assumption is accounted for. Kriging is a well suited method in rainfall estimating, because available data points are rarely optimally located with respect to the points to be estimated, and observed values are weighted to provide the best estimates. The main advantages of simple linear kriging are that it is unbiased, optimal and linear (Pedersen et al., 2010).

Inverse Distance Weighted (IDW) is a point data interpolation method that assigns weights to neighbouring observed values based on the distance to the interpolation location and the interpolated value is then weighted average of the observations. This interpolation method is an example of a deterministic interpolation method. Statistical interpolation methods such as kriging are optimal in a statistical sense, but not as robust in data sparse regions. (Ahrens, 2005).

Due to the often low density of rain gauge networks, ground-based measurement of rainfall is usually not spatially representative of an area such as a large catchment. Calculating spatial estimates of rainfall with a network of rain gauges requires measured values to be averaged over a certain area. This is usually done by applying interpolation algorithms such as Thiessen polygons, Kriging, IDW, spline, nearest neighbour or multiquadric equations (Martens et al, 2013; Shen et al, 2012).

The optimization of a rain gauge network is generally done in order to improve the accuracy of rainfall measurements made by the network. In most cases the performance evaluation of a network is usually focussed on reducing the estimation variance of areal rainfall and not on point rainfall across a study area. Although areal rainfall data is sufficient for many applications such as input for hydrological modelling of flood forecasts, it is not ideal for flash flood predictions which are associated with localised convective events that are very intense with high rain rates. Flash flood forecasting is a difficult process, as rainfall estimates of small spatial scales (1km or finer) - and short time scales (1-15min) scales are required. Advancing rainfall estimation for the purpose of flash flood forecasting will bridge the gap between land surface modelling and space-time variability of rainfall (Smith et al., 2007). Thus, high resolution temporal data at a very fine spatial scale is needed in order to confidently predict and control flash floods. In this study the approach proposed by Cheng et al., 2008 was followed. This approach consists of a proposed rain gauge

evaluation, and augmentation methodology which focuses on accuracy assessment of point estimates of rainfall made by each rain gauge across the whole study area.

Tokay et al (2014) found that the study of the spatial variability of rainfall using rain gauge networks usually occur over domains less than 40km in linear extent and that correlation distances are sensitive to number and distribution of rain gauges in the network. Furthermore, Tokay et al (2014) found that highly variable convective storm events have a shorter correlation distance than moderate and more widespread rainfall events. Another factor influencing correlation distance is rain rate. Ciach & Krajewski (2006) found that correlation distances tend to be longer when the rain rate is more than 3 mm h⁻¹. It was concluded by Tokay et al (2014) that the correlation distance is the measure of the spatial variability of rainfall and that it should be considered as an essential parameter in designing a rain gauge network.

Designing an optimal rain gauge network, with regards to the number and location of rain gauges, has been recognized as a fundamental part of monitoring rainfall distribution in both large and small catchments (Shah et al, 1996; Shen et al, 2012).

1.3 Research objectives

The overall objective of this research is to characterize rainfall using a high density rain gauge network in the Mooi River catchment. Specific objectives to meet this goal are to:

1. Evaluate the use of syphon tipping bucket rain gauges to characterise rainfall
2. Characterise the spatial variability of rainfall in the Mooi River catchment.
3. Optimise rain gauge network density for the South African Highveld using the Mooi River catchment as a case study.

1.4 Research design

Rainfall data is commonly used for applications in climatology, meteorology, hydrology, precision farming, agriculture, flash flood forecasting, weather forecasting, runoff modelling, stream flow predictions and water resource management to name a few. The space-time resolution of data required for each of these applications varies considerably. Thus, there is a need for more spatially distributed measurements of rainfall and other hydrological variables which have a higher spatiotemporal resolution (Martens et al, 2013).

The traditional instrument of choice used in rainfall measurements is rain gauges. They are considered to make very accurate measurements of rainfall and their measurements are relatively easily obtainable, despite their known uncertainties. However, the number of gauges that is

operated by SAWS has decreased severely over the last few decades. Since 1940's the number of rain gauges in operation has declined from 4500 to 1750 by the year 1999 with less than 600 of these reporting daily and in good stead (Figure 1-13). This calls for an improvement in the country's ability and infrastructure to monitor rainfall over large areas in close to real-time as well as better spatial resolution of rainfall estimates in order to obtain more accurate catchment rainfall estimates under convective conditions (Terblanche, et al., 2001).

For this study a high density rain gauge network was installed in the Mooi River catchment on the Highveld of South Africa (Figure 1-14). The data obtained from the network was quality controlled and the general characteristics of rainfall in the Mooi River catchment were investigated. The spatial variability of rainfall was also determined for various accumulation periods using Pearson's correlation coefficient. Using information derived from the spatial variation analysis of rainfall, a methodology was proposed using geostatistics to evaluate and if necessary, augment the existing high density rain gauge network in order to achieve the desired spatial distribution of rain gauges that are necessary for various applications. This methodology consists of using a kriging variance to assess the accuracy of rainfall estimation by using an acceptance probability that has to fall within a certain range of values. Determining the probability of the estimation error helped to prioritize the base network from the existing network of rain gauges. The base network consists of rain gauges in the existing network that have acceptable accuracy. The remaining non-base gauges could then be relocated and if necessary new gauges could be added in order to achieve acceptable estimation accuracy across as much of the catchment area as possible.

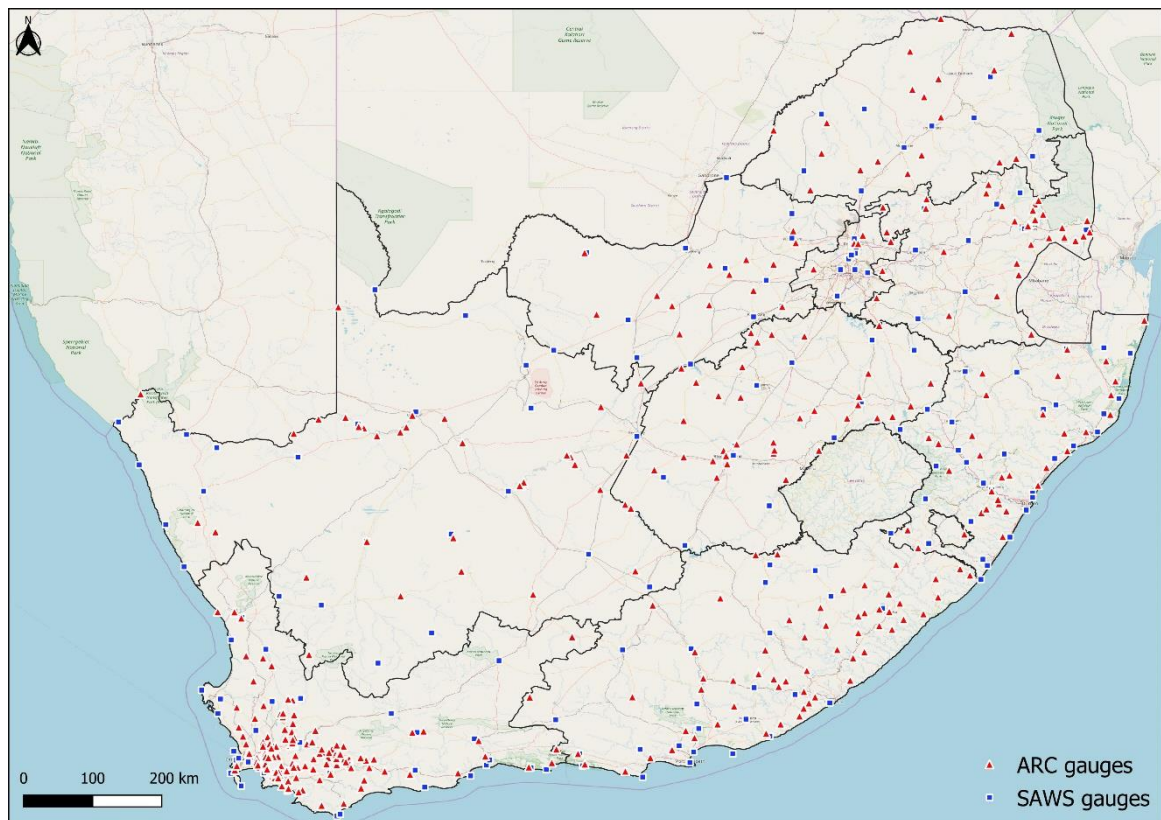


Figure 1-13: The South African rain gauge network including all Automatic SAWS and ARC reporting stations. Map projection: WGS 84 / UTM zone 35S

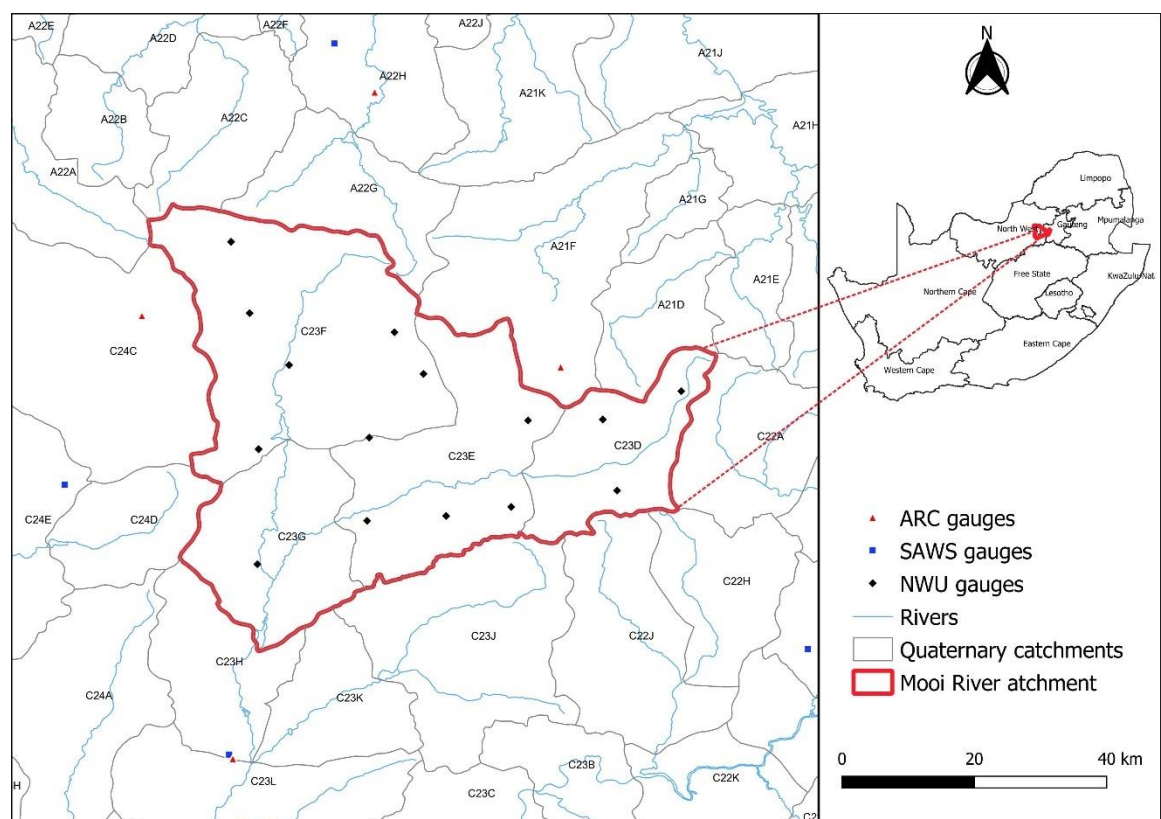


Figure 1-14: The Mooi River catchment, the rain gauge network installed in it and the various quaternary catchments. Map projection: WGS 84 / UTM zone 35S

CHAPTER 2 DATA AND METHODS

2.1 The characteristics of the Mooi River catchment

The Mooi River catchment (Figure 2-1) is situated on the South African Highveld 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 km² and stretches from 16 km north of Potchefstroom towards Derby in the north and eastward towards the highly populated Witwatersrand area of Gauteng. The climate of the catchment is moderate with predominately summer rainfall occurring between the months of October and March (see Figure 1-3 and Figure 1-4). The Mooi River catchment receives on average 600 mm of rainfall every year (Lynch et al., 2001 and Schulze, 1997). The rainfall over the catchment is highly variable especially during large convective storms in the summer months which, from time to time cause severe hail and flash flooding with potentially millions of Rand's damage (Dyson, 2009).

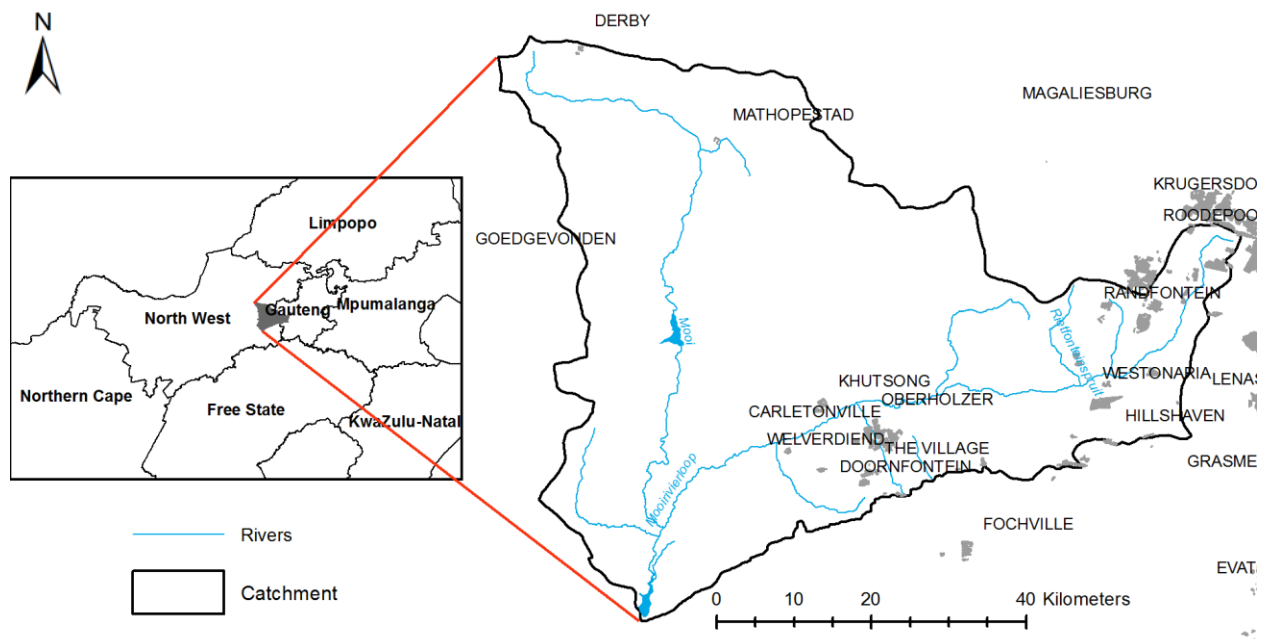


Figure 2-1: The location of the Mooi River catchment in the Highveld of South Africa. Map projection: WGS 84 / UTM zone 35S

The Mooi River catchment varies in terrain elevation from 1344 metres above mean sea level at the banks of the Mooi River to 1795 metres in the densely populated greater Johannesburg area to the east of the catchment. The topographical variation is the steepest in the eastern parts where the catchment meets the escarpment of the Wit Waters Rand (Figure 2-2: a). The eastern parts of the catchment are also the most densely populated and it is especially in these areas where flash flooding occurs the most due to the steep topographical gradient.

The land use of the Mooi River catchment consists mainly of natural grasslands, cultivated farm land, and urban areas in the Carletonville region and greater Johannesburg areas (Figure 2-2 b). The main economic activities in the Mooi River catchment are predominantly agriculture in the form of crop farming and gold mining. Information on the climate and rainfall variability of the Mooi River catchment is of great importance to these two industries and a rainfall monitoring network in this area will provide a great deal of information on rainfall for these two industries.

Rainfall measurements are extremely important for the agricultural sector as only 12% of the country is deemed suitable for rain-fed crops (WWF, 2010). A high density rain gauge network that can provide reliable and accurate rainfall information and is spatially representative of the rainfall regime of the Mooi River area, will therefore add tremendous value to the agricultural sector as a whole. The main agricultural activities in the Mooi River catchment include dryland farming of grain crops and livestock farming with cattle (Figure 2-2 c).

The geology of the Mooi River catchment consists mainly of carbonate rocks (Figure 2-2 c) called dolomites. Dolomites are known to form 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 into a massive. Sinkholes form when rainfall percolates into the soil and reacts with carbon dioxide to create slightly acidic water which moves into the cracks of the dolomitic rock and slowly dissolves the rock until the cavities which are formed in the dolomite collapses in on itself and forms a sinkhole. Because rainfall plays such a big part in the formation of sinkholes the rain gauge network will also assist in monitoring their formation of sinkholes by comparing the amount and rate of rainfall over time with the formation of sinkholes. Doing this will help to identify the relationship between rainfall and sinkhole formation in the area in order to ultimately predict the conditions that are prone to sinkhole formation.

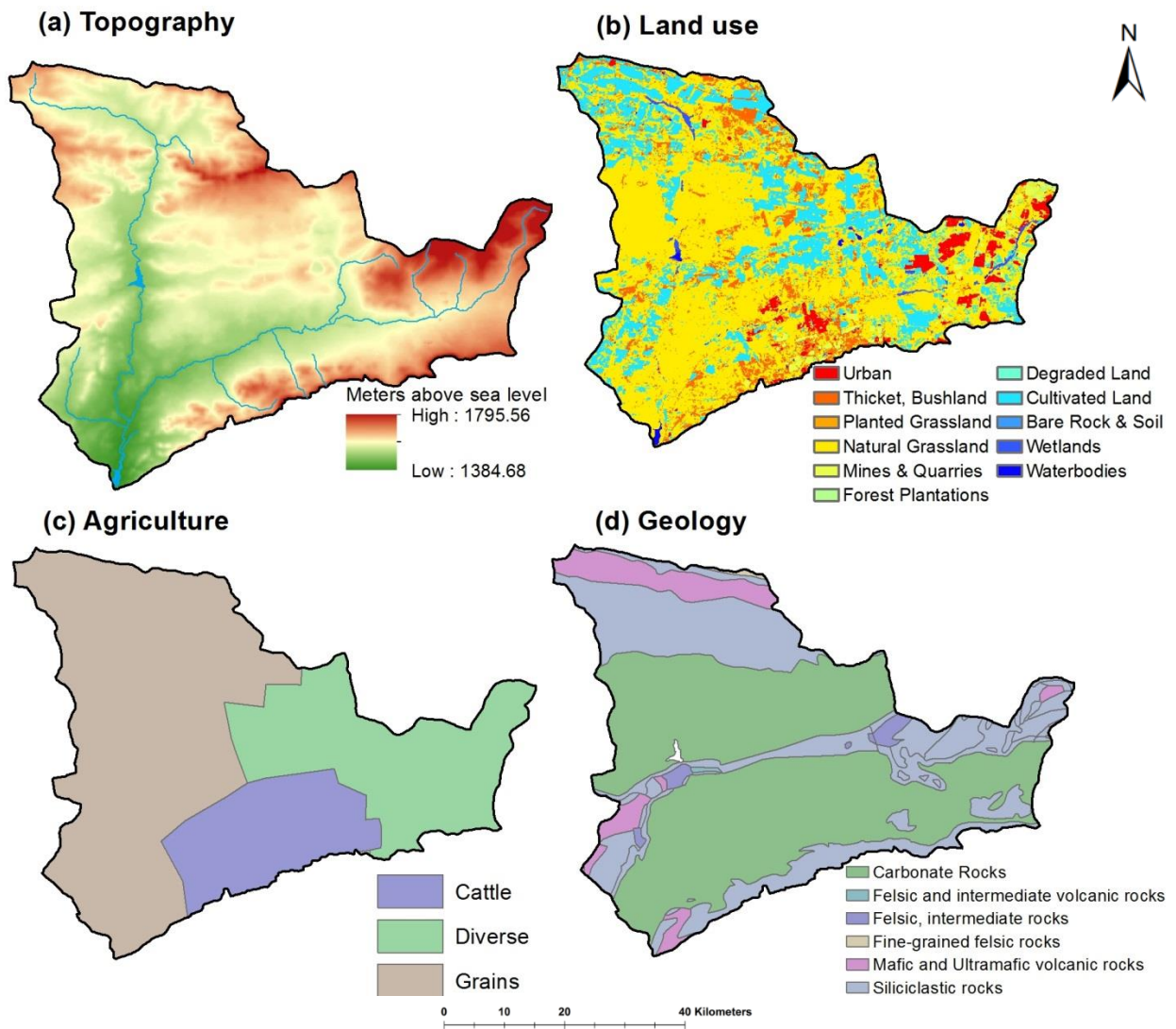


Figure 2-2: The Topography (a), land use (b), agricultural activities (c) and geology of the Mooi River catchment (Data obtained from the NWU geo-database). Map projection: WGS 84 / UTM zone 35S

The Mooi River Catchment and its surrounding areas are also home to several SAWS and ARC rain gauges (Figure 2-3). Most of these SAWS rain gauges can give historical daily rainfall records back to the 1960's. There are also a few of the SAWS and ARC rain gauges that provide data of 5 minute rainfall records from the late 1990's until present. The SAWS rainfall monitoring network in the Mooi River catchment area is a great advantage to the newly installed Mooi River catchment 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.

Other valuable research infrastructure that is present in the Mooi River Catchment area is the substantial number of DWS flow gauges in the Mooi and Mooirivierloop river and Wonderfontein Spruit (Figure 2-3). Data from these flow gauges can provide a clear picture of runoff water that

accompanies rainfall events. By using the data from rain gauges and flow gauges in the Mooi River catchment, in depth hydrological and climatological studies can be done in the future of the variable and dynamic nature of water in the Mooi River Catchment.

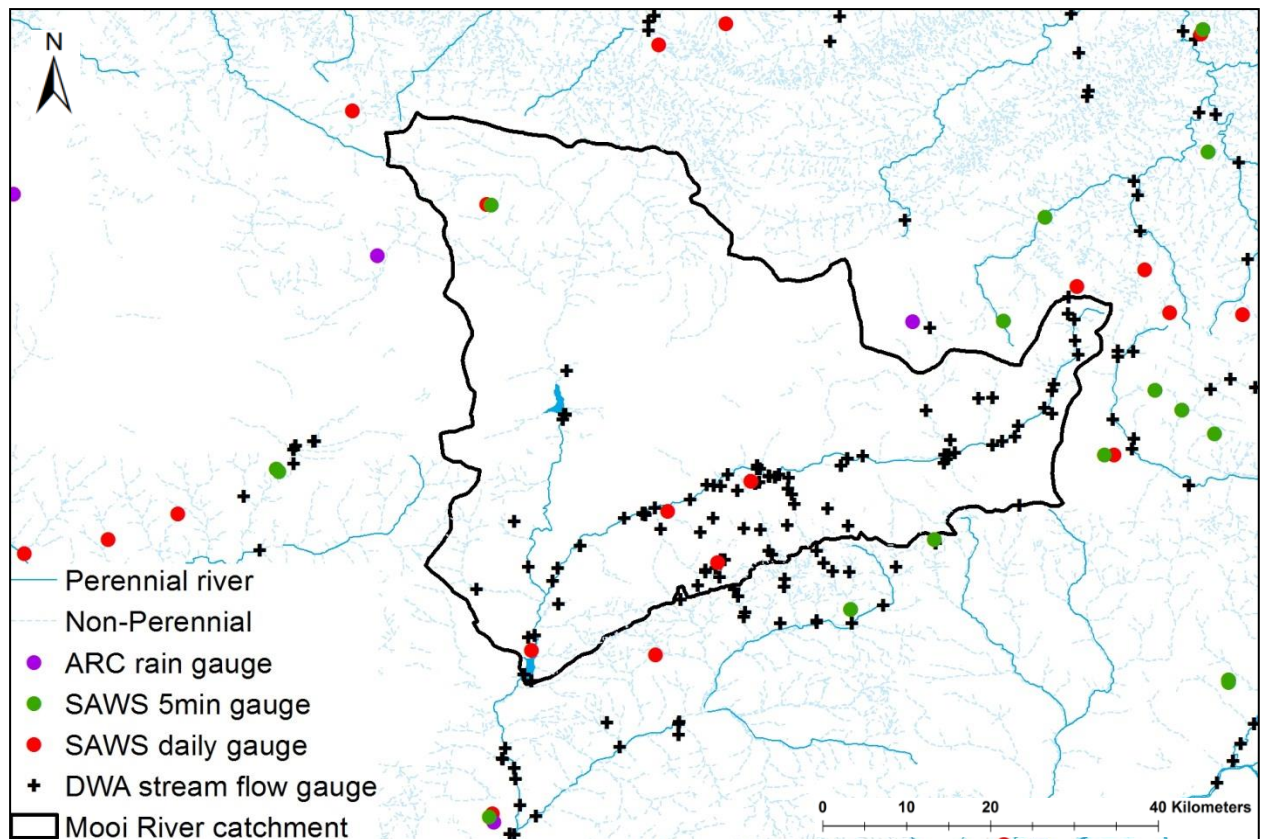


Figure 2-3: The SAWS and ARC rain gauge network and DWS flow gauges in the Mooi River catchment area. Map projection: WGS 84 / UTM zone 35S

The Mooi River catchment is also situated within the coverage area of two SAWS S-band weather radars (Irene- and Ottosdal radar) as well as the newly installed C-band weather radar installed by the North-West University just outside of Potchefstroom (Figure 2-4). The combinations of 3 weather radars and a high density rain gauge network, makes the Mooi River catchment an ideal study area for research purposes. Rainfall estimates from the combined data of all these instruments will be extremely advanced and can contribute a great deal of information to the water resource management, mining, agricultural and various other sectors that are found in this area.

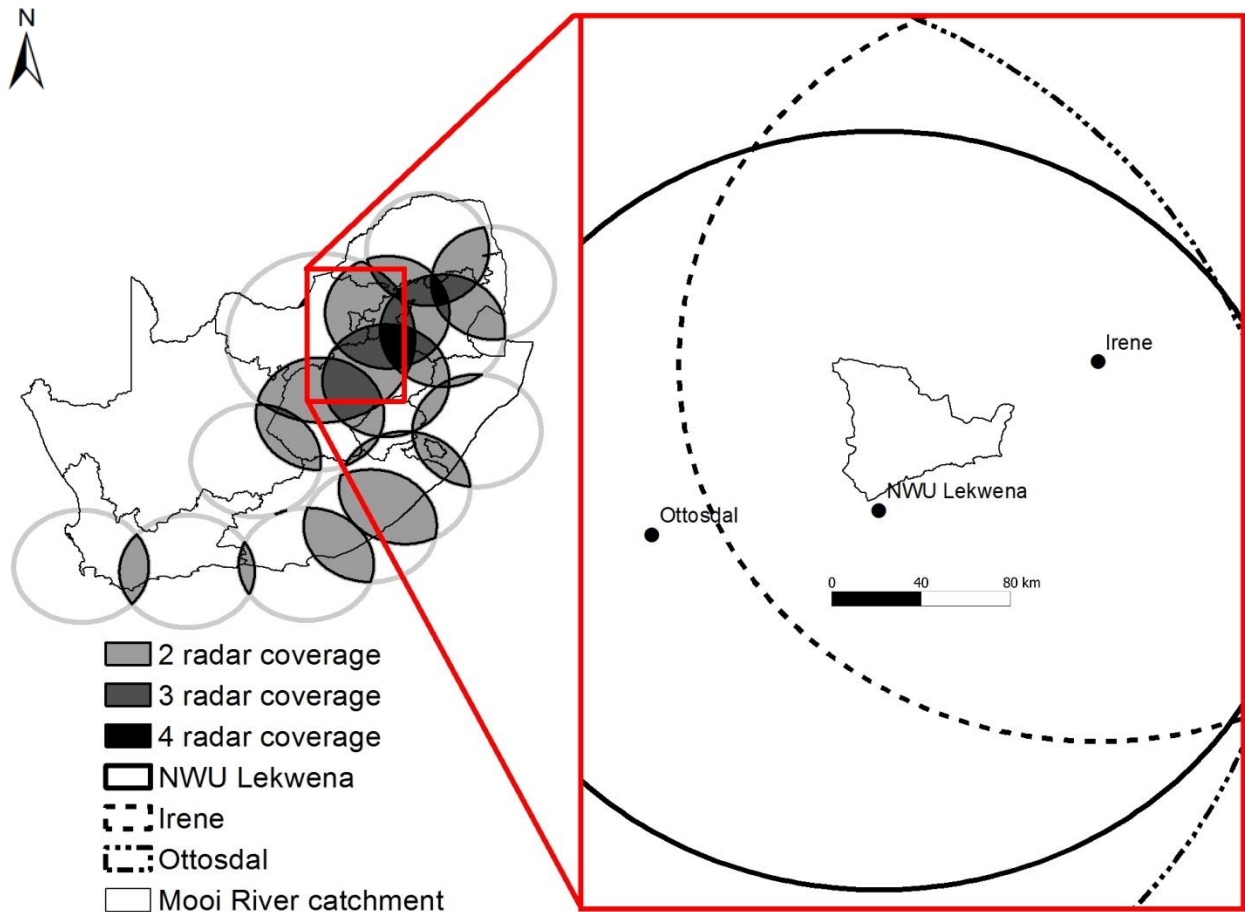


Figure 2-4: The Mooi river network falls within the 200 km coverage area of 2 SAWS S-Band radars (Irene and Ottosdal) and the newly installed NWU Lekwena C-Band radar. Map projection: WGS 84 / UTM zone 35S

2.2 The Mooi River rain gauge Network

The Mooi River rain gauge network from here on referred to as MRGN was installed in the Mooi River catchment during 2014. A network of 15 TB3 tipping bucket rain gauges was installed over the catchment area and they are regularly visited for data collection and maintenance. High resolution data from March 2014 to June 2015 were recorded at each rain gauge site and used in this study.

All of the rain gauges in the western and northern parts of the catchment are located on commercial farms where dryland farming is practised (Figure 2-2 c). Rainfall measurements are of critical importance to these farmers as their livelihood depends on it. The other rain gauges in the catchment are mostly located in urban built up areas where flash flooding regularly occur during large convective storms and can cause considerable damage to infrastructure and in some cases even loss of life.

Figure 2-5 illustrates the location and extent of the completed MRGN. The rain gauges are spread out over the catchment as best as possible and cover a whole variety of land use and topographical locations (Figure 2-2).

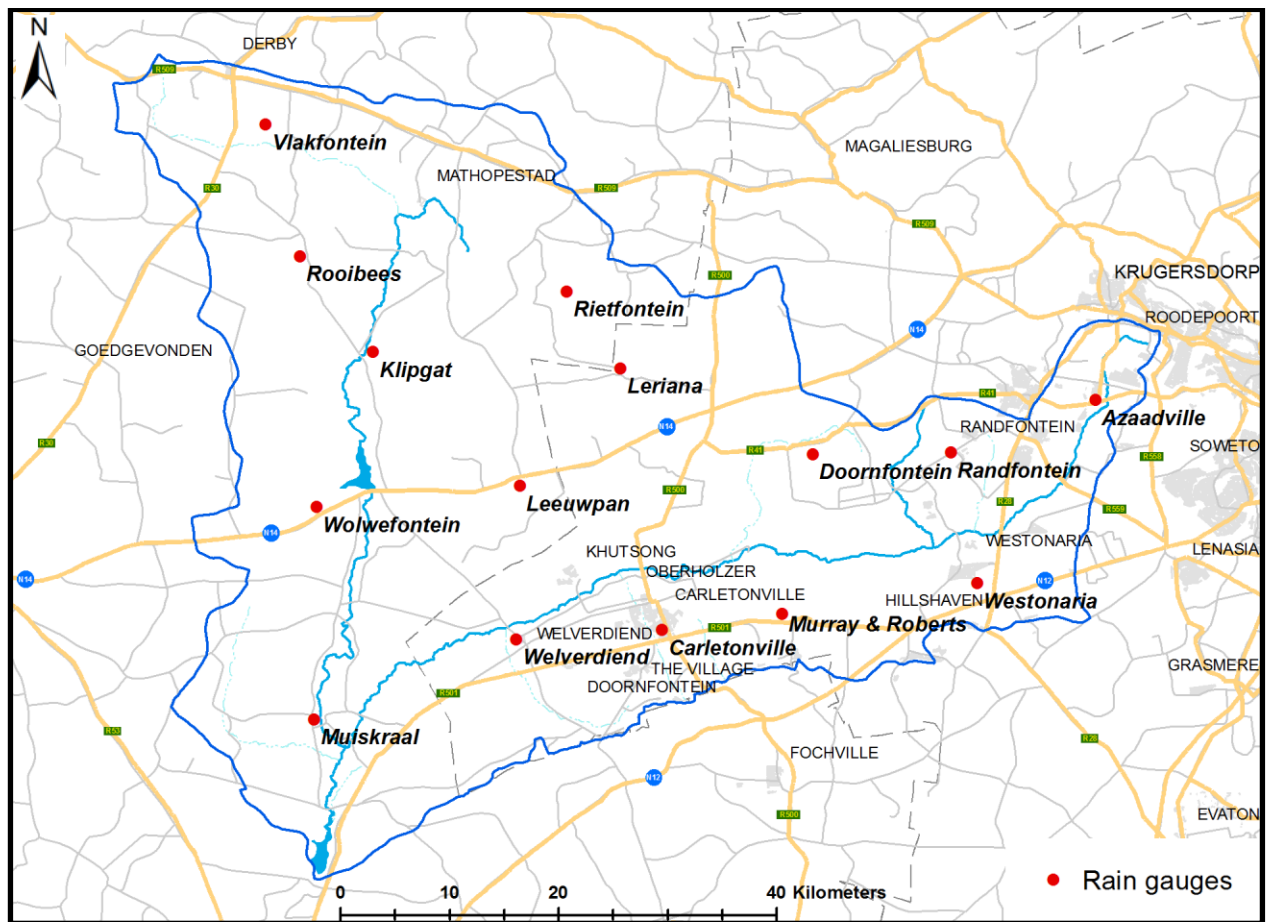


Figure 2-5: The MRGN consisting of 15 tipping bucket rain gauges.
Map projection: WGS 84 / UTM zone 35S

2.2.1 The TB 3 tipping bucket rain gauge

The rain gauges installed in the Mooi River catchment are the TB 3 tipping bucket rain gauge manufactured by HYQUEST SOLUTIONS PTY LTD. The TB 3 tipping bucket rain gauge is also the same type of rain gauge as used by SAWS and ARC at all of their automated weather stations in and around the Mooi River catchment. TB 3 gauges can provide very accurate high resolution data of rainfall in real time. The accuracy of the TB 3 gauge is also not affected by rainfall intensity and it has stable long term calibration (HYQUEST SOLUTIONS PTY LTD, 2014).

The TB 3 gauge is a simple mechanical device with a 200 mm diameter receiver that measures rainfall directly at discrete locations on the earth's surface. The measuring system of these rain gauges are based on two tipping buckets on a horizontal pivot which tips over once rain of 0.2

mm is collected in one of the two buckets (Figure 2-6). The TB3 gauge proves to be a rugged, reliable gauge. It has protection against bugs and only slightly under-measures high rain rate events in excess of 500 mm/h. The stated maximum rain rate that this gauge can measure is 700 mm/h. The manufacturer also states that an accuracy of $\pm 2\%$ for rain rates between 25 and 500 mm/h can be achieved by this gauge. Comparisons with other gauges have yielded favourable results (HYQUEST SOLUTIONS PTY LTD, 2014).



Figure 2-6: The measuring system of the TB 3 tipping bucket rain gauge.

Another feature of this rain gauge is the integrated syphon mechanism (Figure 2-7), 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 & Mekis, 2008).

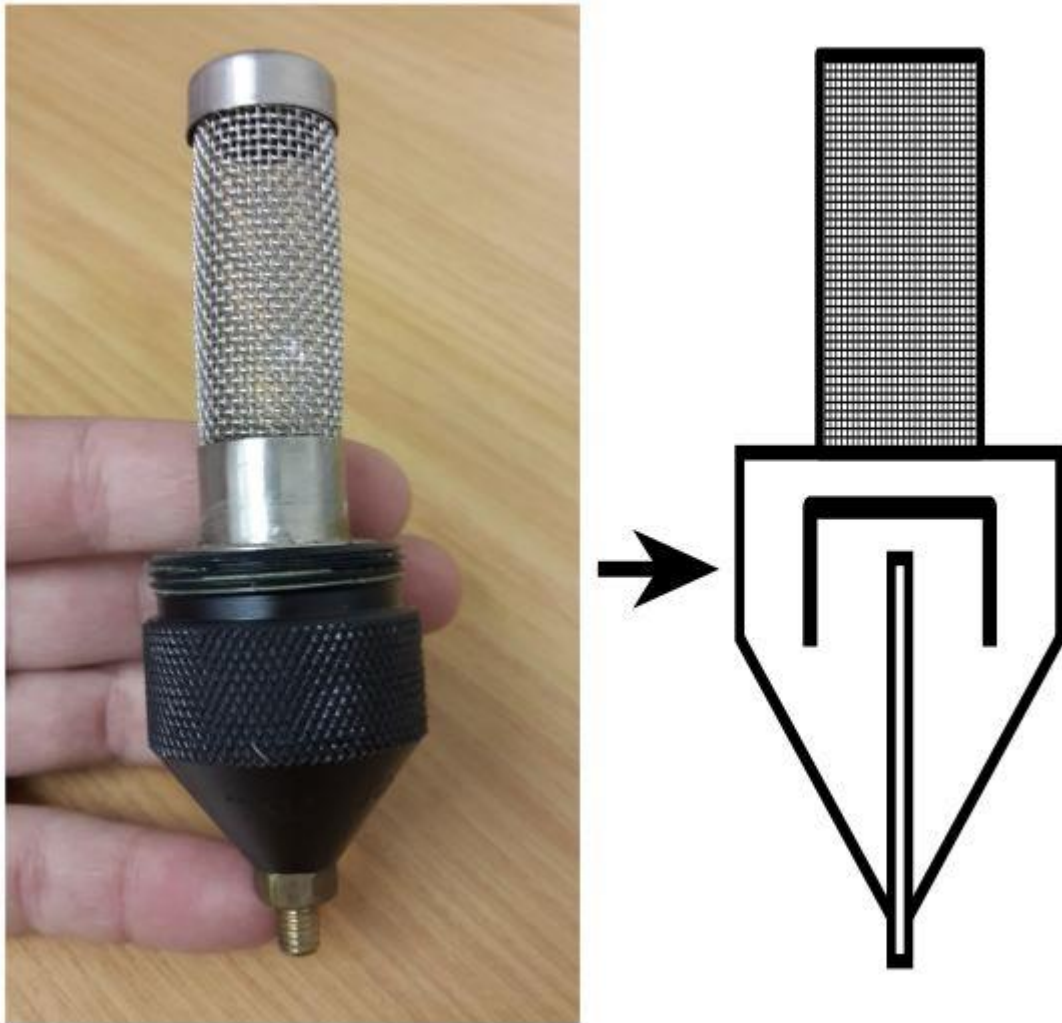


Figure 2-7: The syphon mechanism of the TB 3 tipping bucket rain gauge.

Other features of interest on the TB 3 rain gauge are the various filters and screens fitted to it which keeps debris and insects out of the essential parts of the rain gauge in order to prevent stoppages and jamming of parts such as the pivot of the rain gauge (Figure 2-8).



Figure 2-8: The catch filters of the TB 3 keeps debris and insects out of the mechanisms of the gauge.

Figure 2-9 illustrates the setup of each rain gauge in the MRGN. Rain water is collected in the funnel of the gauge and is passed through the syphon into one of two tipping buckets. Once 0.2 mm of water has accumulated in bucket, a tip occurs, and the other bucket starts to fill up. This tipping action causes a magnet connected to the tipping buckets to send an electrical pulse via the read switch to a data logger. Each of the rain gauges in the MRGN is equipped with an Electronic System Development, Elog1 data logger that records the time of each tip to the nearest second. The logger contains an 8 gigabyte memory card which has the capacity of recording 6.5 million tips corresponding to 1 305 882 mm of rainfall. The gauges of the MRGN are also equipped with a 12-volt lead crystal battery that is charged with a solar panel through a solar regulator. One of the great advantages of this gauge setup is the power usage of the data loggers. Even when a solar panel is out of order or the solar regulator breaks, the gauge can still continue recording rainfall for up to 6 months by solely relying on the battery power. This makes the gauges of the MRGN an ideal setup for remote locations where frequent maintenance visits are not possible.

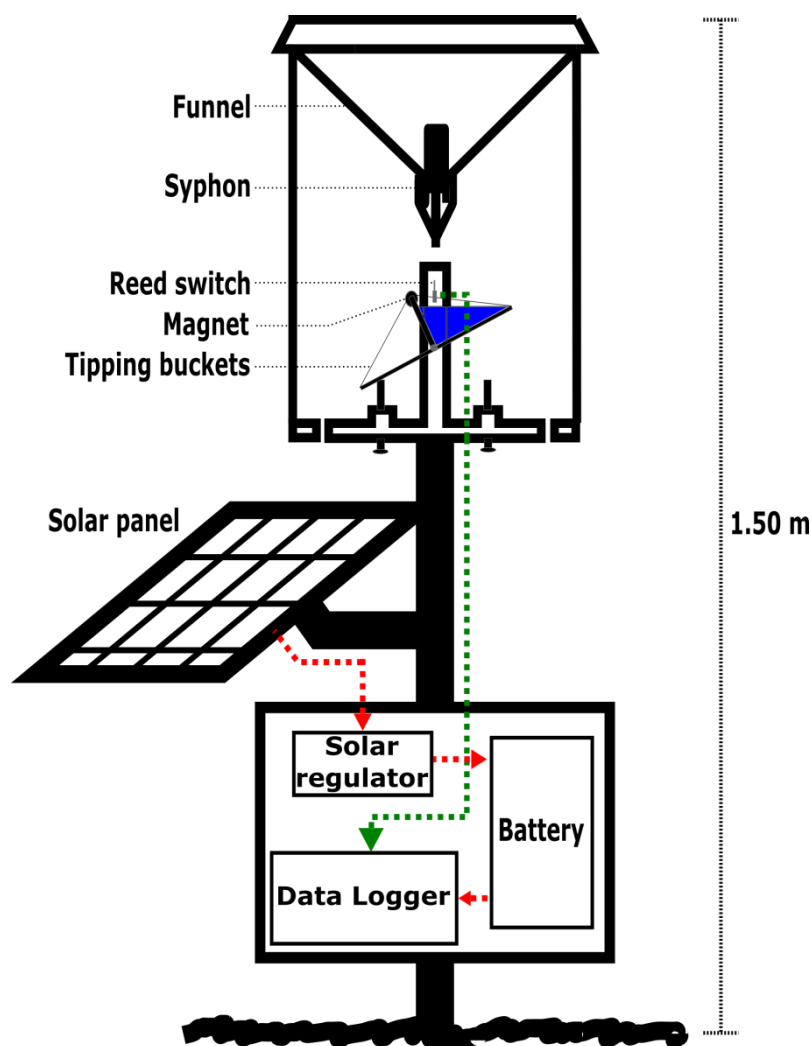


Figure 2-9: The schematic of the rain gauges installed in the MRGN showing the TB 3 gauge, solar panel and the utility box containing the solar regulator, battery and data logger.

2.3 Selecting a site for each rain gauge

The first step of installing the MRGN was to evenly distribute the 15 rain gauges over the Mooi River catchment in order to cover as much of the surface area as possible. This was done by dividing the Mooi River catchment into 15 sections of equal area (Figure 2-10). The surface area of the Mooi River catchment is 3294 km², thus in order for the gauges to be representative of the whole study area each gauge had to cover a 219.6 km² area. This is consistent with the WMO, 2008 criteria for minimum gauge density which states that there should be at least one gauge for every 5750 km² in a undulating topographical region such as the Mooi River catchment (for the WMO, 2008 minimum gauge density criteria refer to Table 1-2 on page 11). The delineation of the Mooi River catchment into 15 areas of equal size was subsequently done by dividing the area into 15 hexagons of 219.6 km² (Figure 2-10). The hexagon shape was chosen as it gives the best representation of equal area. The 15 hexagons that were either fully or near to full, within the

border of the catchment polygon were chosen as the areas in which a rain gauge would ideally be situated. The general rule of thumb was that one rain gauge in each hexagon over the catchment area will be representative enough in order to obtain an even distribution of rain gauges over the Mooi River catchment area.

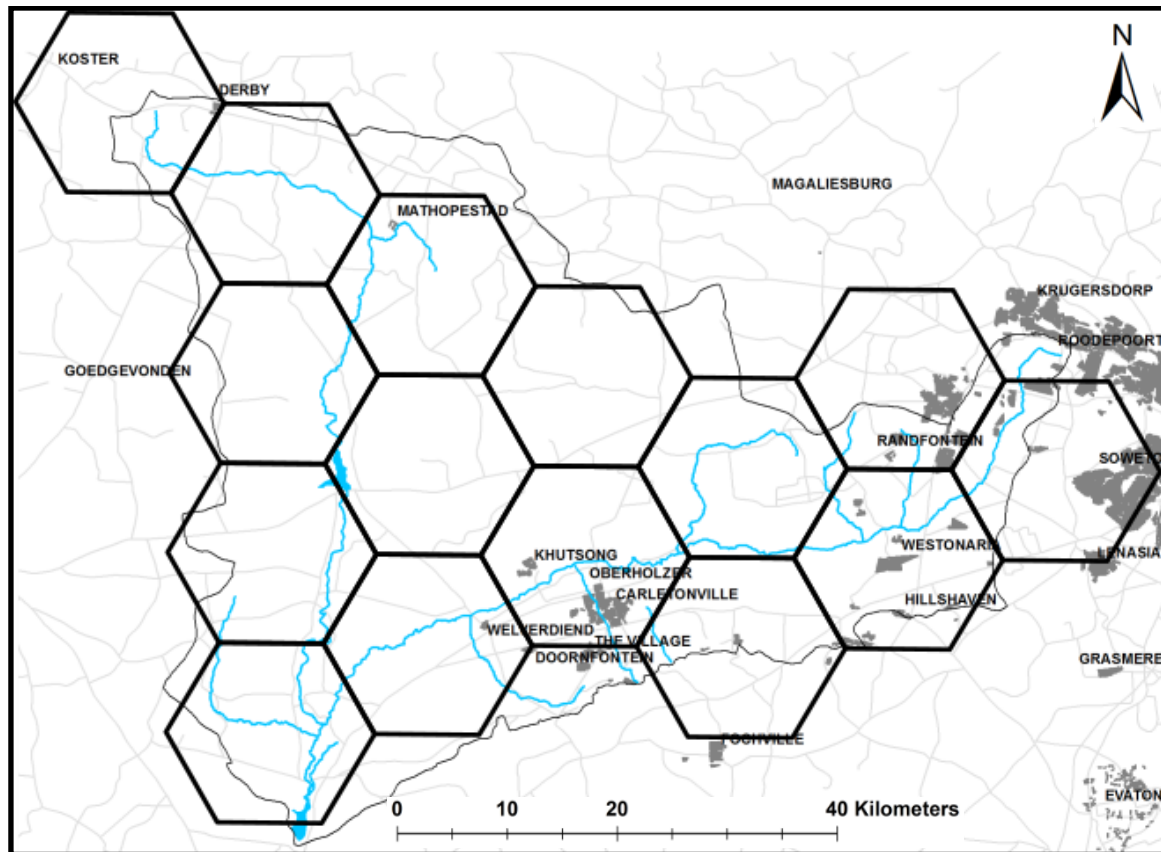


Figure 2-10: The Mooi River catchment divided into 15 areas of equal size (Black hexagon). Each hexagon represents an area of 219.6 km². Map projection: WGS 84 / UTM zone 35S

The second step was to find an appropriate site for each gauge in the areas shown in Figure 2-10. Ideally a rain gauge should be placed at a site where it would represent the actual rain falling on the surrounding area. However, this can be difficult to achieve in practise due to various factors which can influence the representativeness of a rain gauge (see section 1.2.2.1. on page 12 for reference to these factors). Careful considerations have to be taken when selecting the site to place a rain gauge. Thus, the WMO, 2008 criteria for selecting a site were followed:

- Each rain gauge should be placed on level ground where there are no obstructions within a 30° angle around the top of the gauge (see Figure 1-12 on page 12).
- The wind speed at gauge level should be uniform and as small as possible.

- Rain gauges should be away from buildings, trees and other obstructions that could possibly affect its measurements.
- Rain gauges should always be exposed so that the orifice is level to the ground.
- Sites on a slope and with objects that can produce significant wind disturbances should be avoided.
- Hard surface such as concrete should also be avoided when a rain gauge site is chosen, as these surfaces can cause excessive splashing. Ideally the ground surrounding a gauge should either be short grass or gravel.

These criteria were applied to every rain gauge site in the MRGN. There were however also other criteria that had to be considered before a rain gauge site was chosen.

- Each site had to be secure because the risk of vandalism or theft could lead to a loss of data.
- Many of the gauges had to be placed in remote locations so accessibility to each site (even for vehicles without 4 x 4) was very important.
- With the farm owner's permission, each gauge had to be placed on site so that it conforms to both the gauge siting criteria as well as the owners' preferences. This made it a difficult process as the best site according to WMO, 2008 criteria was not necessarily always the best site for the owner and in many cases compromises had to be made.
- Another criterion for site selection was telecommunication. Modern stations make use of GPRS/GSM modems for real-time monitoring purposes. For this reason, it was important to verify that the selected site had sufficient cellular network strength.
- Gauges should not be placed in areas, especially on farms where livestock such as cattle or other animals can disturb the rain gauge. If there were no other alternatives the gauge had to be protected by a fence such as the one shown in Figure 2-12.
- Areas where irrigation is used should also be avoided. This is a problem that was first realised after some of the rain gauges were placed and these gauges then had to be moved to a more suitable location (Figure 2-11).



Figure 2-11: The Westonaria gauge with a sprinkler in the background that could possibly cause false reading to be recorded.



Figure 2-12: The Muiskraal gauge is fenced off to deter livestock from disturbing it.

After inspecting each site, a suitable location that conformed to all the above-mentioned criteria was chosen to place each of the rain gauges. In the urban areas such as Welverdiend, Carletonville, Westonaria and Azaadville, schools were chosen as sites for the rain gauges due to their accessibility, security and open areas on the sport fields. One of the gauges had to be placed in the mining area of Sibanye Gold which made it difficult because the whole area is part of the mining operations and thus an alternative site had to be found. The training academy of Murray and Roberts was chosen due to its security and accessibility. In the Randfontein area one of the gauges was installed on a small holding that had adequate open spaces and security. The

rest of the 10 rain gauges were all installed on farms. Although these farms have more than enough space for the rain gauge to be properly placed according to WMO, 2008 criteria, security remained the main concern and as a result most of these gauges had to be installed in or around the farm house where in some cases the perfect site was not always found and compromises had to be made, such as, placing the gauge closer to the house or building which is not ideal.

The third step was the physical installation of the rain gauges. The rain gauges are mounted on a 1.50 m high steel stand (Figure 2-9) and placed in an open area that is level to the ground and is free from obstructions such as trees and buildings. Once the right spot on site is found to place the rain gauge, a 50x50x50cm hole is made in the ground and the stand of the rain gauge is then placed in the hole and filled with ready mix concrete in order to thoroughly secure it in the ground. This helps to stabilise the rain gauge against the effects of wind and to prevent theft. Once the concrete has set and the gauge is properly in place, the gauge itself is levelled with the built in spirit level. This ensures that the rain gauge captures rainfall in the most accurate way possible. The data logger is then programmed so that the exact time South African Standard Time (SAST) is reflected on the logger. The solar panel is then checked to ensure that it is working properly and the voltage of the 12V battery is tested. Once all the equipment is checked and tested on site, the rain gauge is put into operation and left until data is collected.

For more information on each rain gauge site such as the contact number of the owner/person in charge of the site, the coordinates and installation date of the gauges as well as a photographic view and topographical map of each site, refer to Appendix A on page 94.

2.4 The calibration and maintenance of the MRGN

The TB 3 rain gauges are calibrated by HYQUEST SOLUTIONS PTY LTD prior to dispatch, each of the MRGN gauges were calibrated in the laboratory before being installed in the field. The calibration of each rain gauge was tested using a model 52260 rain gauge calibrator manufactured by RM Young (Figure 2-13). This is a simple calibration device developed especially for field calibration of rain gauges. The calibrator serves as a tool for the adjustment and continuous supply of a constant flow rate. This device is equipped with 3 nozzles of different diameter which are used to simulate rainfall entering the gauge under various intensities (50, 75, 100 mm/hour).

For calibration, tap water is used. During the calibration process the data logger records each signal produced by the tipping action of the buckets. According to the calibration chart of the TB 3 rain gauge, 500 ml of water should, under calibrated circumstances, result in 79.99 tips of the buckets in the rain gauge. This ensures precise conversion of the bucket tips to actual rain rates. Thus, each of the gauges was checked for consistency with the above-mentioned criteria. With

each of the subsequent visits to the rain gauges, this process was repeated to ensure that each rain gauge remains properly calibrated.



Figure 2-13: Laboratory and field calibration of rain gauges. The gauge is calibrated before deployment in the lab (left photo). The calibrator has three nozzles to simulate different rain rates (Middle photo's). The gauge being calibrated in the field (right photo).

A rain gauge that is left unmaintained will very soon be unable to make measurements with the degree of reliability required by researchers making use of the data. During the course of this study, more than 4500 km were travelled, and 150 man-hours spent in maintaining and retrieving data from the MRGN. This means that each rain gauge of the MRGN is visited every 2 months for data collection and maintenance. During each visit the funnel and syphon of the rain gauge is cleaned with a small brush in order to clear out any insects, dust, leaves or other foreign material which could cause blockages of the gauge. On one occasion a spider made its nest in the syphon and effectively blocked any rain water from going through to the gauge and therefore no data was recorded for one and a half months (Figure 2-14).



Figure 2-14: The Leriana gauge, totally blocked due to a spider's nest inside the syphon.

After all blockages are cleared and the gauge is cleaned out, an in-situ calibration test of each rain gauge was performed in order to check if the rain gauges was still properly calibrated. The exact same calibration test that was used in the laboratory was applied in the field (Figure 2-13). Furthermore, the data logger is checked to see if it is still working properly, as time-drifting of the logger programming can become an issue when high resolution real-time data of rainfall is required. The time and date on the data loggers are therefore re-programmed during each visit so that the temporal data derived from the MRGN is always accurate to the nearest second (Figure 2-15).

During each site visit the rain gauge was checked to see if it was securely attached to the stand and level to the ground and to ensure that the stand was still firmly implanted in the ground. All cables were also checked to ensure that they were still firmly connected to the gauge, data logger and solar panel and if necessary, the contacts were cleaned. Raw data retrieved from the rain gauges were always kept in its original format and archived on a laptop during each site visit (Figure 2-15). The last important part of the maintenance procedure was to take notes during each site visit. During site visits the gauge might accidentally be disturbed, causing tips to be falsely recorded. Thus, the time of arrival and departure on site was important to note because any tips recorded during this time had to be discounted. Furthermore, the battery voltage was monitored with each site visit in order to check that it was not losing power. And lastly photos were taken of each site.



Figure 2-15: Retrieving data and setting the time and date on the data loggers of the MRGN.

2.5 The data and performance of MRGN

The data of the MRGN was recorded as timestamps and saved to CSV file on a SD memory card. As can be seen in Figure 2-16, the timestamps were recorded as either \$RD, \$ED or \$TD. Each of these provides the user with different information. \$RD indicates when the data logger has been reset. The data logger was usually reset when the time and date was reprogrammed. As previously mentioned, time drifting can cause the gauge to record data that is out of sync with the real time and thus it has to be re-programmed with each visit to the gauges. The \$TD is what is called timed interrupted data and what this basically means is that the logger records an automatic timestamp once every 12 hours. This is important for the data quality control process as the \$TD gives an indication of whether there was a problem with a data logger that did not work or if there was no rain falling in that moment in time which could be recorded. The \$ED is called event interrupted data and this is a timestamp recorded by the logger every time a tip has occurred from one of the two tipping buckets in the rain gauge. Thus every \$ED timestamp represents actual rain being recorded by the gauge. During data analysis each \$ED timestamp can then be assigned a value of 0.2 mm which is the size of each bucket. When looking at the raw data it is therefore important to remember that \$ED timestamps are the main parameter of interest and that \$RD and \$TD does not give information on the actual rainfall, but they do give important additional information on the workings of the data logger.

Function	ID	Tip number	Date	Time	Event count
\$RD	0006	0000000000	2013-11-27	13:30:10	00000,!!
\$ED	0006	0000000001	2013-11-27	13:30:13	00001,!!
\$TD	0006	0000000002	2013-11-27	13:30:00	00001,!!
\$ED	0006	0000000003	2013-11-27	13:30:16	00002,!!
\$ED	0006	0000000004	2013-11-27	13:30:17	00003,!!
\$ED	0006	0000000005	2013-11-27	13:30:18	00004,!!
\$RD	0006	0000000006	2013-11-27	13:58:02	00004,!!
\$ED	0006	0000000007	2013-11-27	13:58:04	00005,!!
\$ED	0006	0000000008	2013-11-27	13:58:04	00006,!!
\$ED	0006	0000000009	2013-11-27	13:58:05	00007,!!
\$RD	0006	0000000010	2014-03-14	14:49:38	00007,!!
\$RD	0006	0000000011	2014-03-14	14:51:06	00007,!!

Figure 2-16: An example of raw data from the MRGN.

The data set that was used in this study consisted of 1-minute time series data from the 15 gauges of the MRGN during the period of November 2014 to June 2015 as well as daily and 5-minute time series data from SAWS gauges with a long time series (in the period of 1920 to 2014) that are located in and around the Mooi River catchment.

In this study Upton and Rahimi, 2003's easily programmable diagnostic checks were used to do quality control on the data from the MRGN. The main focus of the data quality control procedure was to identify and eliminate any errors in the data that may have been falsely recorded or in the case of blockages, prevent actual rainfall data from being recorded.

Figure 2-17 illustrates tip data for the 15 MRGN gauges during the period of November 2014 - June 2015. Each tip of a rain gauge bucket is represented by a black tick and the grey bar indicates the period of rainfall measurements taken successfully by each rain gauge in the Mooi River catchment. The various gaps in the grey bar of Figure 2-17 indicate that no timestamps were recorded during those periods at the Welverdiend (Des. 2014 – mid-Jan.2015), Leriana (mid-Feb. 2015 – June 2015), Vlaktefontein (Nov. 2014 – Des. 2014 and again during Feb. 2015) and the Carletonville (mid-Apr. 2015 – June 2015) gauges respectively. These gaps were the result of either the gauge being offline due to a problem with the data logger or in the case of the Leriana gauge, loss of data due to theft.

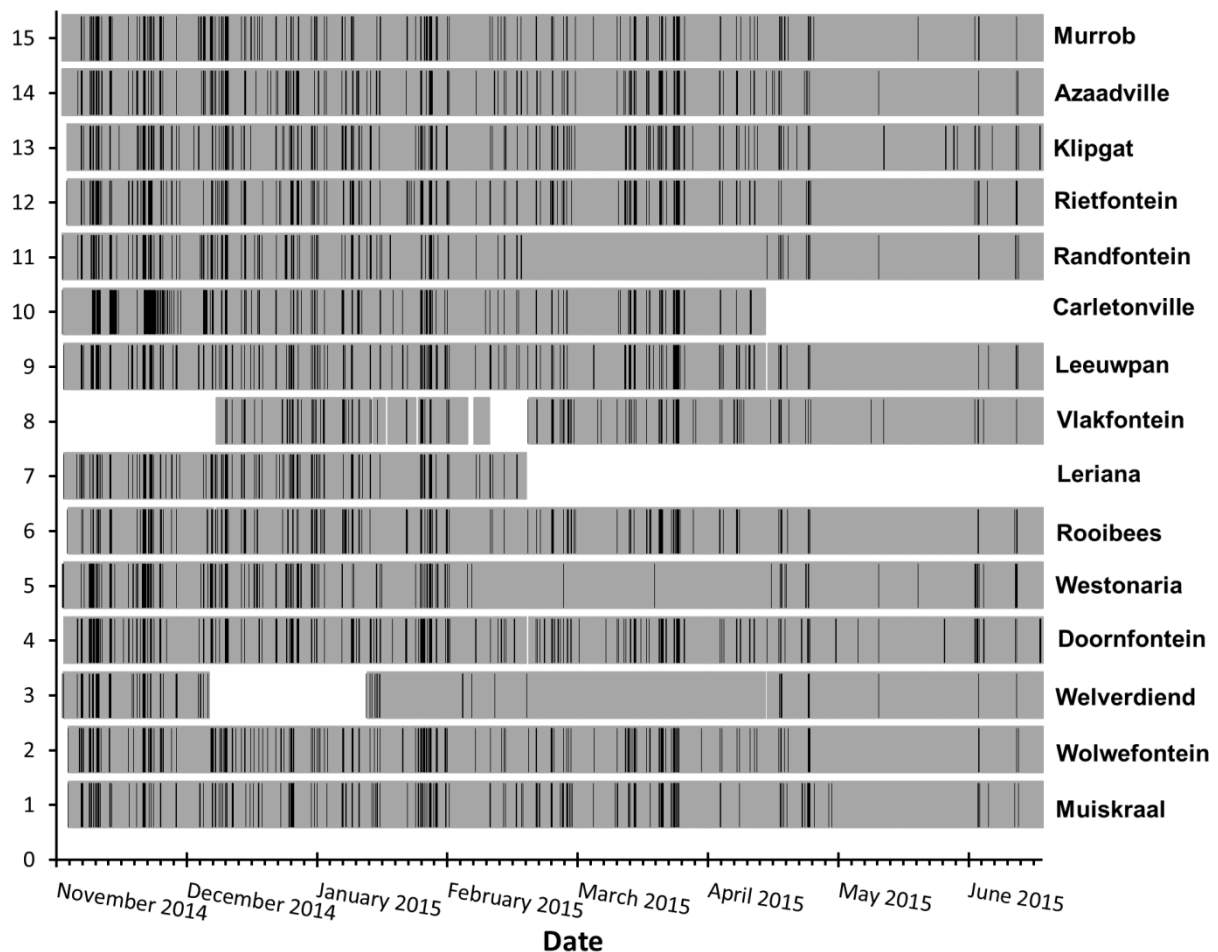


Figure 2-17: Each tip of the rain gauge bucket is represented by a black tick and the grey area indicates the period of rainfall measurements taken by each rain gauge in the MRGN. White gaps indicate that there is no data available or recorded for that period.

Table 2-1 shows the percentage of time that the network was either blocked, offline or working. During the period of November 2014 - June 2015 the 15 gauges in the MRGN were fully operational for 86% of the time. 11% of the time there were more than one gauge that was offline. These offline periods were mostly associated with software malfunctions, theft or animal induced damage. Lastly it was found that blockages caused gauges to miss-record or not record real rainfall at all 3% of the time.

Table 2-1: The percentage of time that each rain gauge in the Mooi River network was blocked, offline or working

Percentage of installed time				
Nr.	Gauges	Blocked	Offline	Working
1	Muiskraal	0	0	100
2	Wolwefontein	0	0	100
3	Welverdien	45	22	33
4	Doornfontein	0	0	100
5	Westonaria	0	43	57
6	Rooibees	0	0	100
7	Leriana	0	34	66
8	Vlakfontein	0	30	70
9	Leeuwpan	0	0	100
10	Carletonville	6	0	100
11	Randfontein	0	35	65
12	Rietfontein	0	0	100
13	Klipgat	0	0	100
14	Azaadville	0	0	100
15	Murrob	0	0	100
Total		3	11	86

2.5.1 Fast-tipping MRGN gauges

A new approach was used to develop a methodology for semi-automated data quality control on syphon-based tipping bucket rain gauges.

High rain rates and fast-tipping gauges go hand in hand. However, as previously mentioned in section 2.2.1 the TB 3's syphon acts as a flow control to reduce rain rate errors common to tipping bucket gauges. This eliminates the threat of high rain rates causing very fast inter-tip times that are not real to occur. However, deriving rain rates from a tipping bucket rain gauge that has a syphon, such as the TB 3, can be a challenging process. The problem with the syphon is that it occasionally causes double tips to occur that are not associated with high rain rates. This happens because the buffering effect of the syphon causes 0.4 mm of rain water to accumulate in it before the water is released onto the tipping buckets. These double tips are a problem when estimating rain rates because the time difference between double tips are mostly less than 3 seconds which may appear as being recorded during an event with high rain rate, but in reality it is not. Figure

2-18 illustrates the occurrence of double tips in the raw data. From Figure 2-18 it is evident that most of the double tips had inter-tip times of between one and 3 seconds. The Wolwefontein gauge was especially prone to double tips with more than 700 incidents of double tips occurring between two and three seconds. Similarly, the Doornfontein gauge also recorded over 700 tips between one and two seconds. This is almost double the amount recorded by any of the other gauges, thus indicating that double tips were a significant problem with the TB 3 gauge.

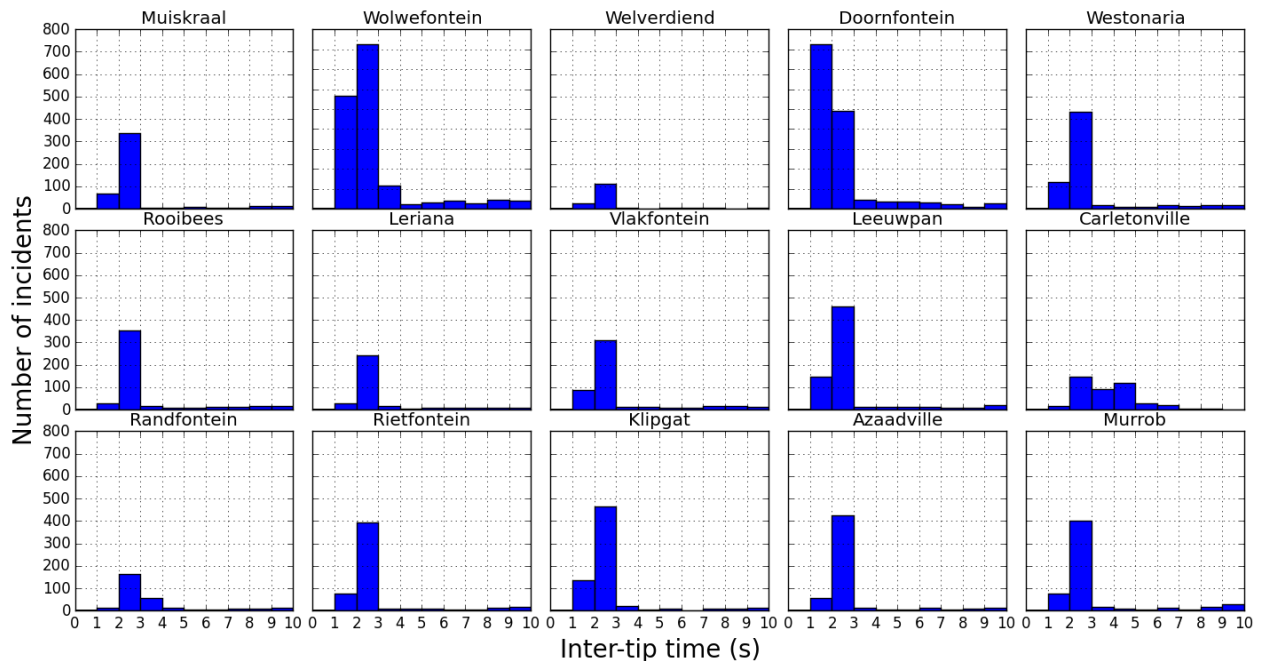


Figure 2-18: The number of incidents where consecutive tips were recorded within 10 seconds of each other (With double tips).

To fix the double tip problem an algorithm was developed to eliminate the double tip problem without losing data. It is important to note that although the double tip causes an error in the inter-tip times of the gauge, real rainfall is still being recorded, thus when eliminating the double tips, no data on the amount of rain that has fallen should be eliminated. Therefore, after each step in the algorithm, the cumulative sum of the rainfall must stay the same. The algorithm identifies double tips when one tip has occurred within 3 seconds of the previous tip. It then assigns an amount of 0.4 mm to the first tip and deletes the second tip, thus adding the 0.2 mm from the second tip to the first tip.

Another aspect that had to be investigated was the actual start of an event⁴. For a bucket to tip, it first has to collect 0.2 mm of rain water. However, the average time it takes for 0.2 mm of rain water to collect in the bucket is unknown. Thus, the start of an event actually happens before the

⁴ Events were identified by a 30-minute gap between consecutive tips.

first tip is recorded. In order to determine the start of an event the time it takes for 0.2 mm of rain water to collect was determined by using disdrometer and a rain gauge that are located next to each other. Using the disdrometer's data to calculate the probability density function of the first 0.2 mm of rain during a rainfall event, it was estimated that it takes on average 8.3 minutes for the first bucket to tip at the beginning of an event. Thus, the average rain rate for the first tip of an event is 1.45 mm h^{-1} . Thus, by adjusting the data according to the average time it takes to record the first tip, the start of a rainfall event could be determined.

Figure 2-19 illustrates the inter-tip times of each MRGN gauge after the double tips were removed. Comparing Figure 2-19 with Figure 2-18, it is clear that there was indeed a significant amount of double tips recorded. In Figure 2-18 all of the gauges recorded the most incidents of inter-tip times between 0 and 3 seconds, whereas in Figure 2-19 most of the inter-tip incidents are recorded between 5 and 10 seconds. Although there are also inter-tip times of more than 10 seconds, for this study it was limited to 10 seconds as false tips are rarely associated with inter-tip times more than 10 seconds.

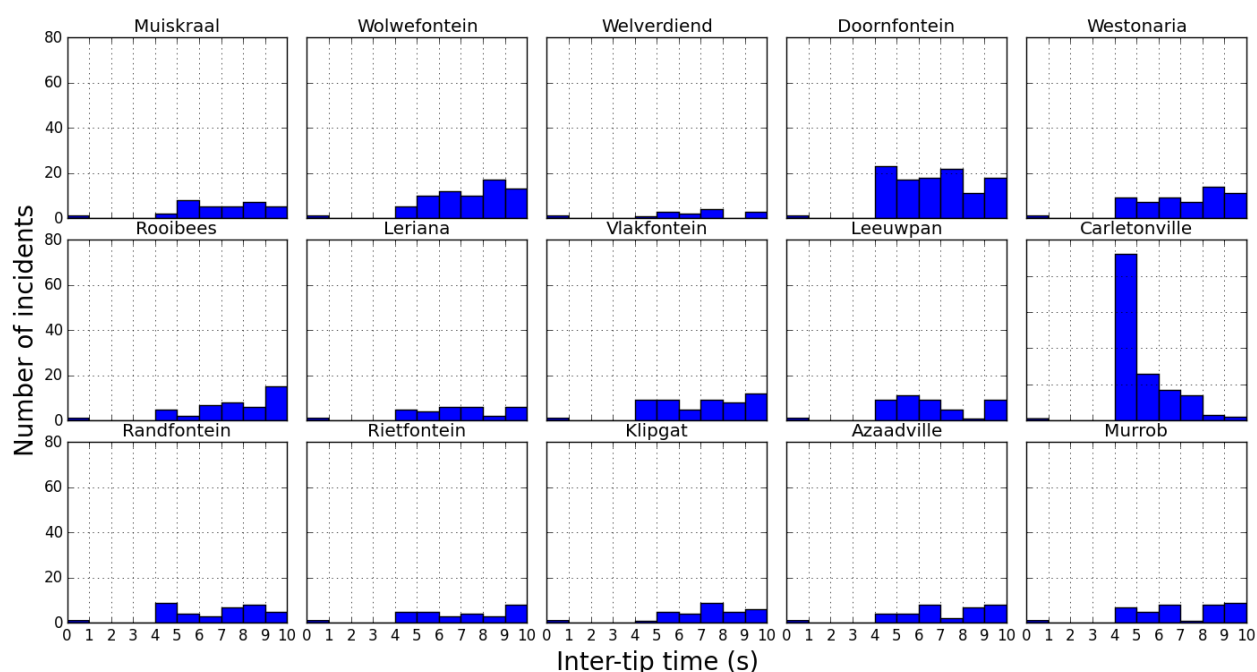


Figure 2-19: The amount of incidents where consecutive tips were recorded within 10 seconds of each other (Without double tips).

Fast tipping times due to high rain rates associated with convective storms in the summer months are generally quite common on the Highveld of South Africa. However, there are instances where fast tips were observed in the data that do not represent genuinely convective rainfall being recorded. As seen in Figure 2-19, the Carletonville gauge had almost 80 incidents where the inter-tip times of the gauge were between 4 and 5 seconds apart. Normally this would indicate that this

gauge was subject to events with very high rain rates, but in this case it cannot be true as none of its co-located gauges had so many inter-tip times anywhere near it. Thus, the data from the Carletonville gauge had to be thoroughly scrutinised in order to find the false tips.

Figure 2-20 is a time series of each tip that a gauge has recorded. Each black tick represents one tip of the tipping buckets. It is evident that there is a sequence of 4 incidents (red boxes) in the time series of the tip data, where the Carletonville gauge recorded far more tips than any of the other gauges. In some cases, it even continued recording tips long after the rest of the network has stopped recording tips. This is evidence that it was not rainfall being recorded, but another force that caused the buckets of the gauge to tip so vigorously.

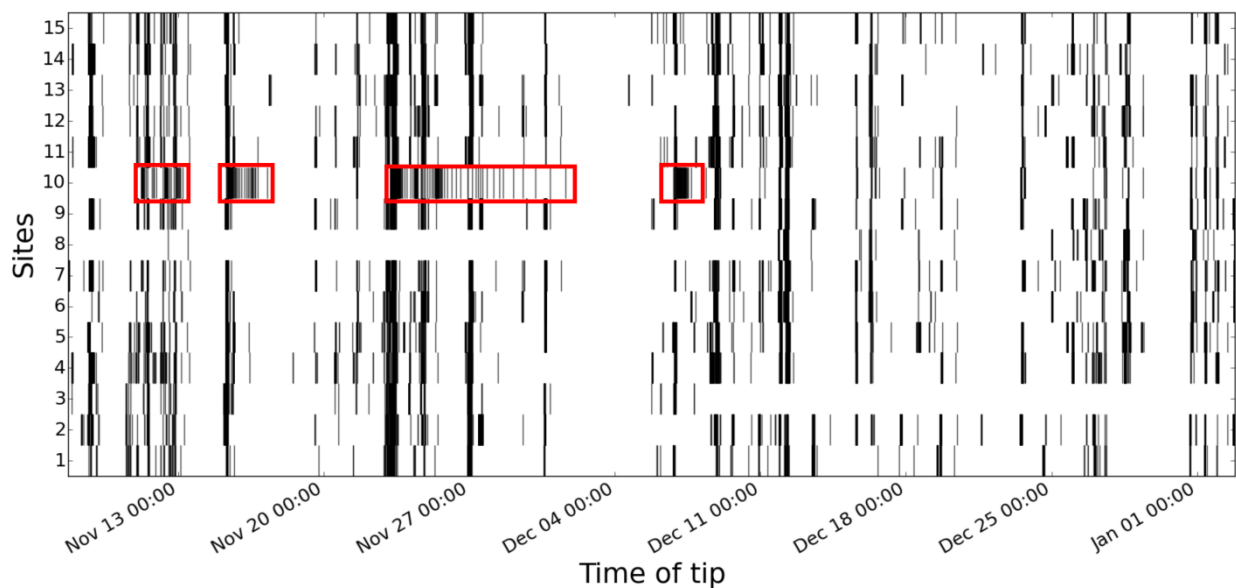


Figure 2-20: Time series showing false (unnatural) tips in red boxes at Site 10 (Carletonville) during the period of 6th of November 2014 to 2nd of January 2015.

Other examples of falsely recorded tips are: the Klipgat gauge (Site 13) recorded 9 tips in the space of 1 minute on 17th November 2014 (Figure 2-21) and the Randfontein gauge (Site 11) recorded 19 tips in the space of 10 minutes on 18th January 2015 (Figure 2-22). None of the other gauges recorded more than one tip on those days, thus it is unlikely that rain was being recorded.

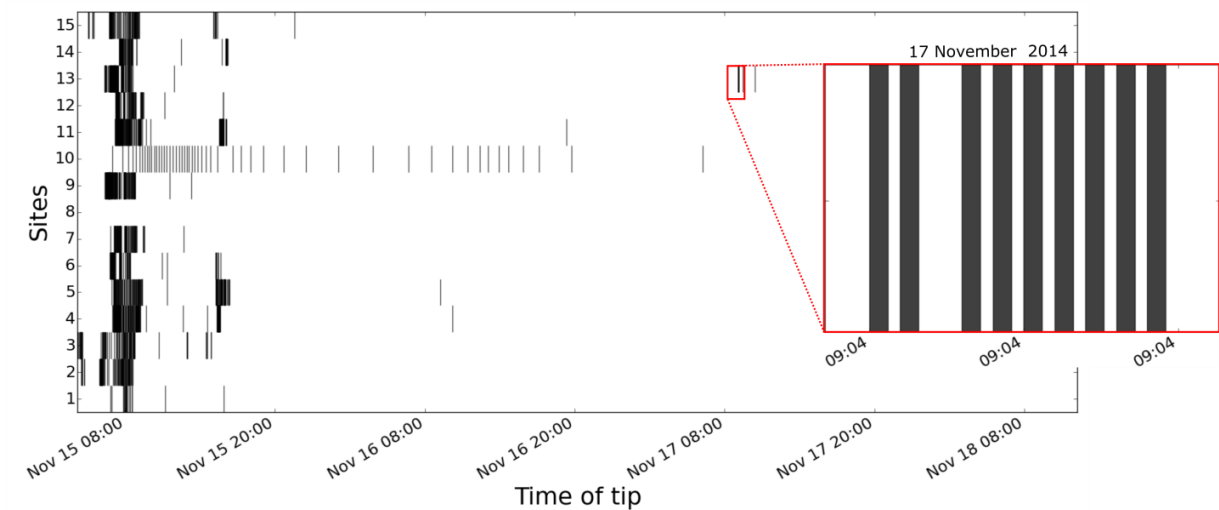


Figure 2-21: Time series showing false (unnatural) tips in red box at Site 13 (Klipgat) during the 17th of November 2014.

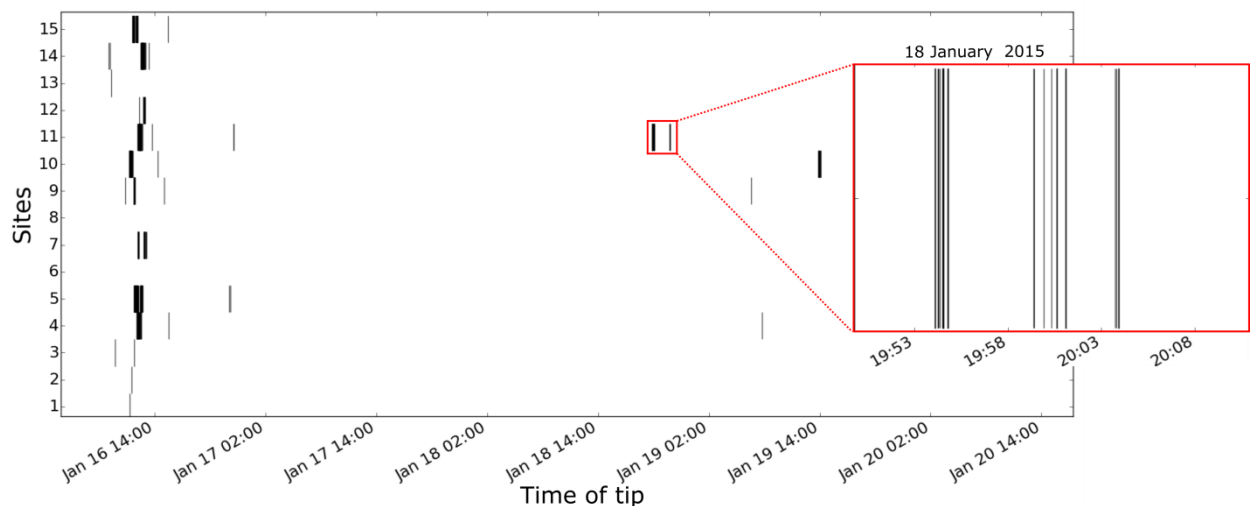


Figure 2-22: Time series, showing false (unnatural) tips in red box at Site 11 (Randfontein) during the 18th of January 2015.

Possible explanations for the false tips shown in the above 3 figures are:

- The Carletonville gauge (Figure 2-20) is located in an open field at a school where strong winds could have shaken the gauge or as it is at a school, the students could have jerked it out of curiosity.
- The Klipgat gauge (Figure 2-21) is located on a farm where farm animals such as the horses or cattle could have scratched themselves with the gauge causing it to be jerked or it could also be strong winds.
- The Randfontein gauge (Figure 2-22) is located on a small holding where the owner breeds with big mastiff dogs, thus the false tips can possibly be the result of dog jerking the gauge. Wind effects are eliminated because this gauge is well sheltered from the wind.

The false tips shown in Figure 2-21 and Figure 2-22 were found through the process of manually going through the data set and looking for inconsistencies in the data. Although this process of manual data quality control is a difficult and time consuming process, it is still necessary because these incidents will generally not show up in the inter-tip time plots of the gauge and thus they can easily be overlooked. All of the false tips identified in this section were ignored in the following discussion.

2.5.2 Malfunctioning MRGN gauges

Most of the gauges in the MRGN were affected by either: blockages or partial blockages (grass cuttings or insects/spiders) or software or other electronic failure. Some were affected by both. In two of the cases (see the Welverdiend gauge and the Vlakfontein gauge in Figure 2-17 on page 45) a single software failure of the data logger resulted in over a month of rainfall data not being recorded. Since rain gauges were placed in rather remote places, blockages or software failures sometimes lasted for long periods (more than a week) before they could be fixed and brought back online. During the course of this study twelve of the gauges were never blocked, while three gauges (Welverdiend, Carletonville and Leriana) were blocked on one or two occasions. A spider's nest was the cause of blockage at both the Welverdiend and, Leriana while the Carletonville gauge experienced partial blockages from time to time due to grass cuttings. Table 2-1 summarises the proportion of time that each MRGN gauge was affected by these problems.

The raw tip data for each TB tip for this study was summed cumulative tip numbers at each "tip minute." Basically, a tip minute is the minute in which a certain number of tips occurred. These cumulative tip numbers can then be converted into rainfall in millimetres by multiplying tip numbers with the TB size of 0.2 mm.

Non-rainy periods are inferred from the absence of tip records. The TB rain gauge suffers various sampling problems as well as systematic and mechanical error and electrical failures.

When analysing the rain gauge data, each event was analysed separately. Events are classified as periods where rain fell for more than 30 minutes between two dry periods where none of the gauges in the network recorded any tips

2.6 Inter-gauge correlation

Rainfall data from the 2014/2015 rainfall season of gauge observations in the MRGN were summed to 10 different rain accumulation periods ranging from 1 min to 14 days. To determine the spatial variability of rainfall over the Mooi River network, Pearson's correlation r was applied to 77 pairs of gauge records

$$r(X, Y) = \frac{\overline{XY} - \bar{X}\bar{Y}}{\sqrt{(\overline{X^2} - (\bar{X})^2)(\overline{Y^2} - (\bar{Y})^2)}} \quad (1)$$

Where $r(X, Y)$ gives the Pearson product-moment sample coefficient between two variables, in this case the rainfall processes observed at 2 gauge locations, derived from number of pair scores N . The overbars indicate the average values of the sample size N (Habib et al., 2001).

The Pearson's correlation coefficient was estimated for all possible gauge combinations and then plotted as a function of inter gauge distance for 1 min to 14-day accumulations.

2.7 Methods on optimising the high density rain gauge network in the Mooi River catchment

The aim of optimal rain gauge network design is to obtain data at un-gauged location which defines the statistical distribution of the rainfall over the catchment area with enough accuracy for practical use.

The optimum number of rain gauges in a given area can be determined by:

$$N = \left(\frac{C_v}{\varepsilon} \right)^2 \quad (2)$$

(Al-Abadi & Al-Aboodi, 2014).

Where N is the optimal number of rain gauges to be installed in an area, C_v is the coefficient of variation of rainfall as measured by existing rain gauges in the area, and ε is the acceptable degree of error in mean rainfall estimates of the network.

If it was determined by equation (2), that more gauges are necessary in the existing rain gauge network, the additional gauges should be distributed according to the current network's ability to capture the spatial variability of rainfall with acceptable accuracy.

A simple solution is to distribute the additional rain gauges using the standard error of estimation associated with the interpolation of the rainfall field.

2.7.1 Interpolation of MRGN data using Ordinary Kriging

Kriging is the spatial interpolation algorithm used in this study to estimate the unknown values of rainfall at un-gauged locations using the known values of the existing gauges. Kriging is a geostatistical method which yields unbiased estimators with minimum error variance and has been commonly applied to many rain gauge network evaluation and augmentation practices

(Awadallah, 2012; Wei et al., 2014; Chen et al., 2007; Barca et al., 2007; Kassim & Kottegoda 1991 Putthividhya & Tanaka, 2012 and Sivapragasam et al., 2012).

The interpolation algorithm of ordinary kriging can be described where $Z(x)$ is the random variable (in this case rainfall) defined at a certain location x and $\{Z(x), x \in \Omega\}$ is the second-order stationary random field in the spatial domain Ω . To estimate the unknown value of Z at x_0 , using the observed values $z(x_i)$, $i = 1, 2, \dots, n$, at its neighbouring locations the following linear equation can be used:

$$\hat{z}(x_0) = \sum_{i=1}^n \lambda_i z(x_i) \quad (3)$$

(Gentile et al, 2012)

Where λ_i is the weight assigned to a measurement $z(x_i)$. Weights λ_i are calculated with the ordinary kriging system equation:

$$\begin{bmatrix} \gamma_{11} & \dots & \gamma_{1i} & \dots & \gamma_{1n} & 1 \\ \vdots & \ddots & \vdots & \ddots & \vdots & \vdots \\ \gamma_{i1} & \dots & \gamma_{ii} & \dots & \gamma_{in} & 1 \\ \vdots & \ddots & \vdots & \ddots & \vdots & \vdots \\ \gamma_{n1} & \dots & \gamma_{ni} & \dots & \gamma_{nn} & 1 \\ 1 & \dots & 1 & \dots & 1 & 0 \end{bmatrix} \begin{bmatrix} \gamma_1 \\ \vdots \\ \gamma_i \\ \vdots \\ \gamma_n \\ \mu \end{bmatrix} = \begin{bmatrix} \gamma_{10} \\ \vdots \\ \gamma_{i0} \\ \vdots \\ \gamma_{n0} \\ 1 \end{bmatrix} \quad (4)$$

(Gentile et al, 2012)

Where μ is the Lagrange multiplier and γ_{ij} represents the semi variance between $z(x_i)$ and $z(x_j)$.

The standard error or ordinary kriging variance can also be calculated using:

$$\sigma_k^2(x_0) = E \left\{ [Z(x_0) - \hat{Z}(x_0)]^2 \right\} = \mu + \sum_{i=1}^n \lambda_i \gamma_{i0} \quad (5)$$

(Gentile et al, 2012)

CHAPTER 3 EVALUATING THE PERFORMANCE OF SYPHON TIPPING BUCKET RAIN GAUGES ON THE SOUTH AFRICAN HIGHVELD

3.1 Errors associated with tipping bucket rain gauges

Identifying errors in rain gauge estimates are easy when there are several gauges in relative close proximity to each other. In a study done by Ciach, 2003 on identifying local random errors in tipping bucket rain gauge measurements, fifteen gauges were deployed over an area of about 8 m x 8 m. With the gauges so close to each other it was easy to identify errors. However, identifying errors from a single gauge in a large network such as the MRGN is much more difficult as there is no other gauge close enough to validate the estimates.

With conventional tipping bucket rain gauges that don't have syphons, errors are generally prone to occur during high rain rates. High rain rates can cause a bucket to fill up so quickly; that the momentum of the water flowing into the bucket makes it bounce back up again and thus the following tip will be recorded as rain, when in reality the other bucket never filled up with water at all. Therefore, most studies use short inter-tip times to identify errors in their data. However, the fast tip problem during high rain rates is not a problem with the TB 3 gauges installed in the MRGN, as these gauges have a syphon which controls the flow of water into the buckets thus eliminating the occurrence short inter tip times that can occur during high rain rates.

This chapter presents an evaluation of the performance of the TB 3 tipping bucket rain gauges of the MRGN. Over the course of this study there 608 occurrences that had more than 4 incorrectly reported tips. Some sequences lasted abnormally long, with one of them lasting for over 2 months (at the Carletonville gauge). Reassuringly there were no faults found in 7 of the gauges, and only one incorrectly reported sequence found for eight of the other gauges.

3.2 Detecting questionable estimates from a single gauge using high rain rates

It was found that during the course of this study, that several incidents occurred where consecutive tips with inter-tip rain rates of 240 mm h^{-1} or less were never credible, though inter-tip rain rates 144 mm h^{-1} were credible (Figure 2-19 on page 48). A solution which ignores the complexities of high inter-tip rain rates without losing to much information on the amount of recorded rainfall, was to ignore all rain rates that are associated with the highest inter-tip rain rates of 240 mm h^{-1} or less. It may be a reasonable approach to follow for a region where mostly stratiform rainfall occurs, such a procedure would not be acceptable for the convective thunderstorms experienced on the Highveld of South. These storms are commonly associated

with very high rain rates; thus, high inter-tip rain rates will definitely be experienced during such events. Therefore, it is essential to distinguish between high inter-tip rain rates that are credible and those that are not credible. Ciach, 2003 suggested that a possible solution is to assume that the rain rate between consecutive tips of the rain gauge will be similar at one moment and the next and if not there may then possibly be an error.

Thus, the raw rainfall data derived from the MRGN in the form of tip-time series was converted into rain rates with an inter-tip interpolation scheme that computes short-time rain rates with relatively high accuracy.

Suppose that $t_0, t_1, t_2, \dots$, are tip times recorded by a one gauge. The average inter-rip rain rate R_k is then defined using the following formula:

$$R_{interp}(t_0, t_{0+1}) = \frac{V_b}{t_0 - t_{0+1}} \quad (6)$$

(Upton and Rahimi, 2003)

Where V_b is the volume of one bucket which have a resolution of 0.2 mm and $t_0 - t_{0+1}$ is a pair of successive tips.

The processed results are presented for a fragment of a rainfall event that occurred on the 15th of November 2014 (Figure 3-1). The plot shows the time series of rainfall rates for the Leriana gauge (Site 7).

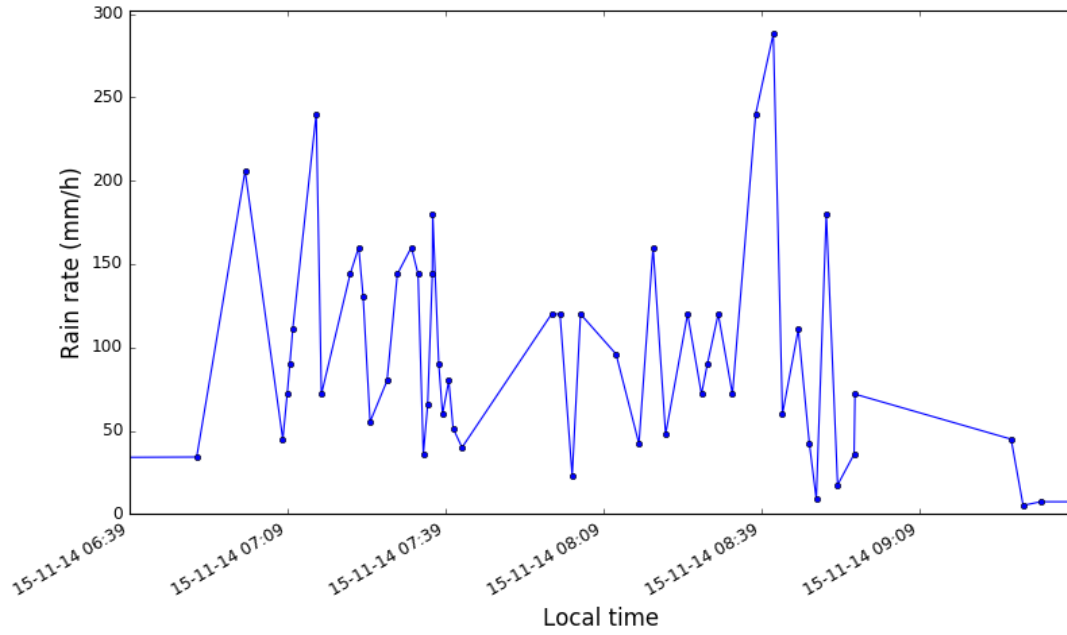


Figure 3-1: An example of the rain rates at Leriana (Site 7) for an event that occurred over the MRGN on the morning of 15 Nov 2014.

Because rain rates changes usually occur slowly between one instance and the next, it can be said that one inter-tip time will approximately be equal to the next inter-tip time:

$$R_t \approx R_{t+1} \quad (7)$$

(Upton and Rahimi, 2003)

During an event with high rain rates the difference between two tips will only amount to a few mm h^{-1} , whereas, at lower rain rates, it might be much more. Thus, it is the ratio of R_t to R_{t+1} that is important, rather than the difference. When $R_t \approx R_{t+1}$ the inter-tip rain rates will have a ratio of 1. This suggests using λ_t given by

$$\lambda_t = |\log_e(R_t/R_{t+1})| \quad (8)$$

(Upton and Rahimi, 2003)

By examining the results after the above equation has been executed, it is evident from the distribution of λ_t that the rain rate at tip t should be rejected if λ_t exceeds 5.

As shown Figure 3-2, for the MRGN data this procedure identified 608 ratios (this is 2.5% out of 24434 incidents in total) that were larger than 5 and thus these inter-tip rain rates could be

classified as questionable. All 15 of the MRGN gauges contributed to the 608 questionable rain rates, with the Azaadvile and Klipgat gauges being the main contributors.

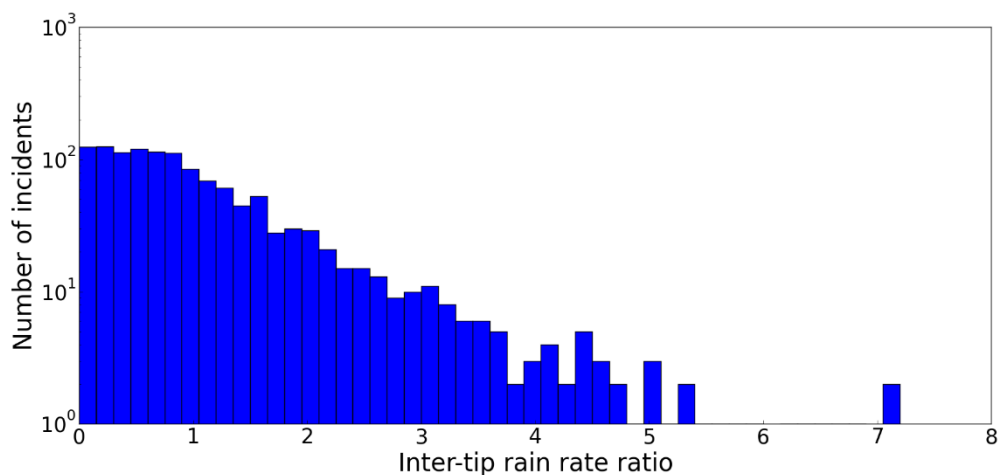


Figure 3-2: The number of incidents with an inter-tip rain rate ratio of between 0 and 8.

Inter-tip rain rate ratios of more than 5 were found at each of the 15 gauges in the MRGN (Figure 3-3). It was, however, clear that the number of incidents with inter-tip ratios of more than 5 were much more common at the Klipgat (Site 13) and Azaadvile (Site 14) gauges.

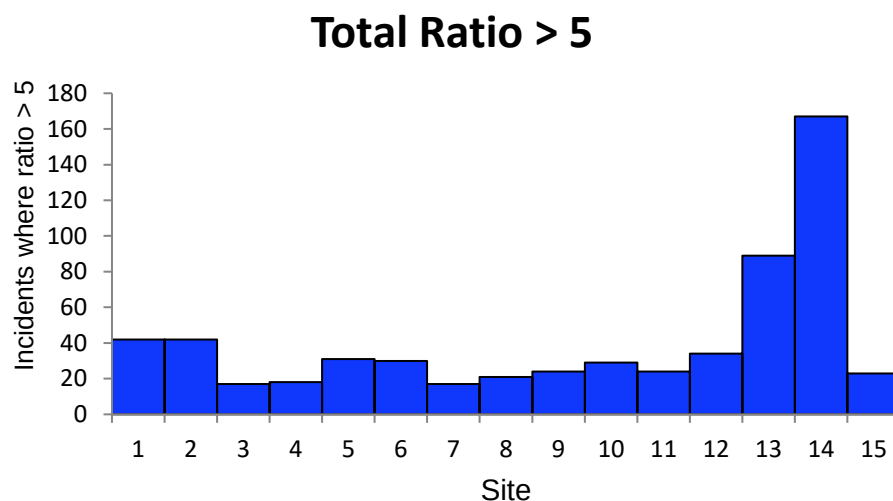


Figure 3-3: Rain gauge sites with an inter-tip ratio of more than 5.

3.3 Detecting questionable tips from a single gauge using tip time series and radar images

Falsely recorded tips of the gauges in the MRGN were also found throughout the network. At the Muiskraal gauge (Site 1) a single tip of the gauge was recorded on the 15th of November 2015

between 15h54 and 15h59 (Figure 3-4). When looking at the Irene radar image for the same time period (Figure 3-5), it was evident that no rain was observed at that time at the Muiskraal gauge, thus the tip that was recorded in Figure 3-4 at the Muiskraal gauge could not have been actual rainfall that was recorded.

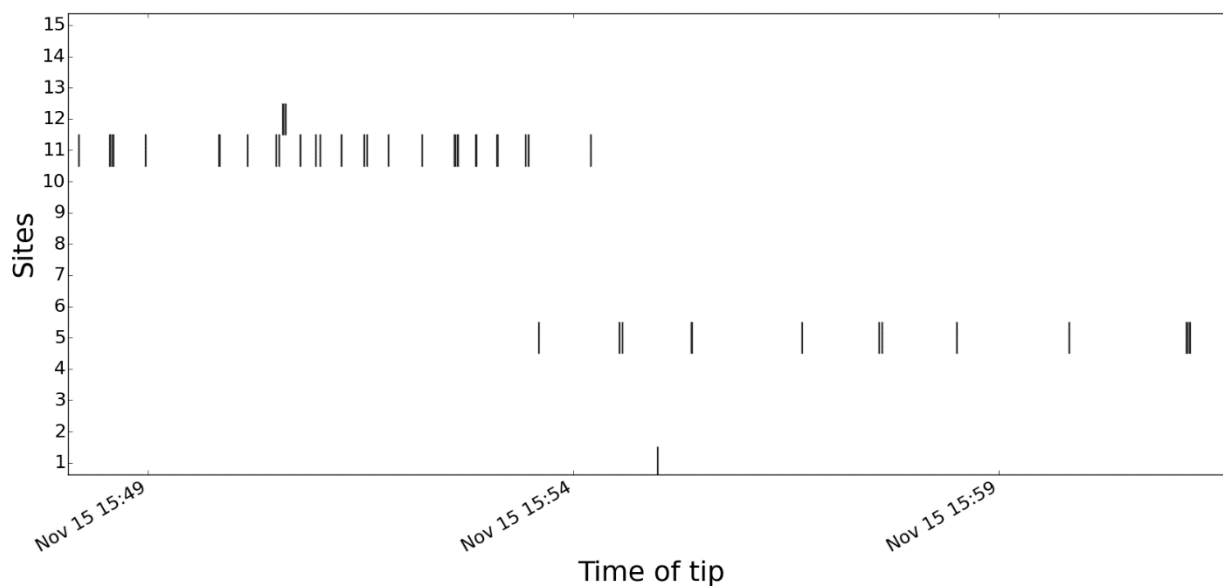


Figure 3-4: Muiskraal (Site 1) tip time series on 15 Nov 2015 (Individual tips are represented by a vertical tick).

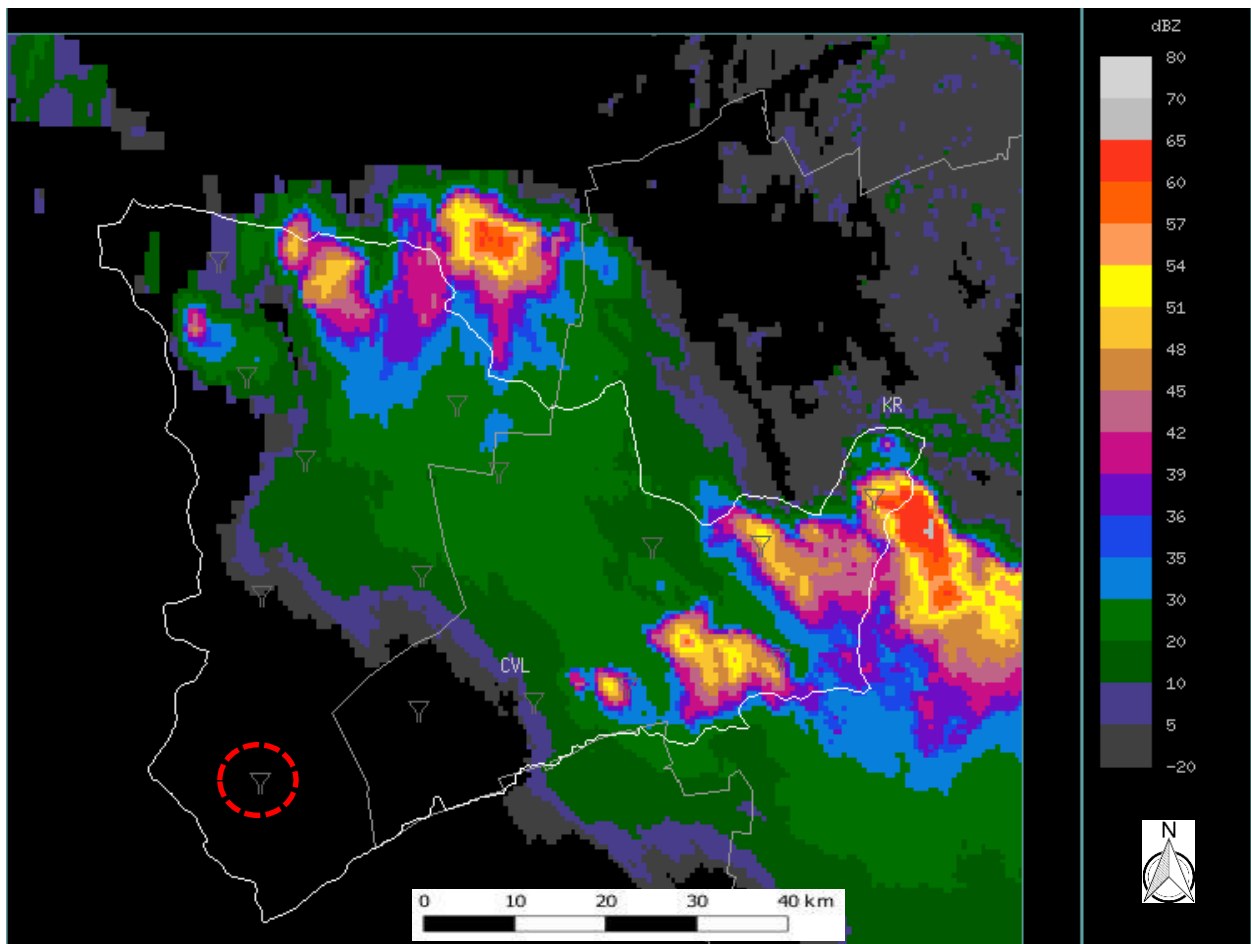


Figure 3-5: Irene radar image of the MRGN on 15 Nov 2015 at 15h56 with the location of the Muiskraal gauge (Site 1) circled in dashed red (Displayed with TITAN software).

The Rietfontein gauge (Site 12) recorded single a tip on 23rd of Jan 2015 between 15h00 and 21h00 (Figure 3-6). Looking at the Irene radar image for the same time period (Figure 3-7), it was evident that no rain was observed at that time at the Rietfontein gauge, thus the tip that was recorded in Figure 3-6 at the Rietfontein gauge could not have been actual rainfall that was recorded.

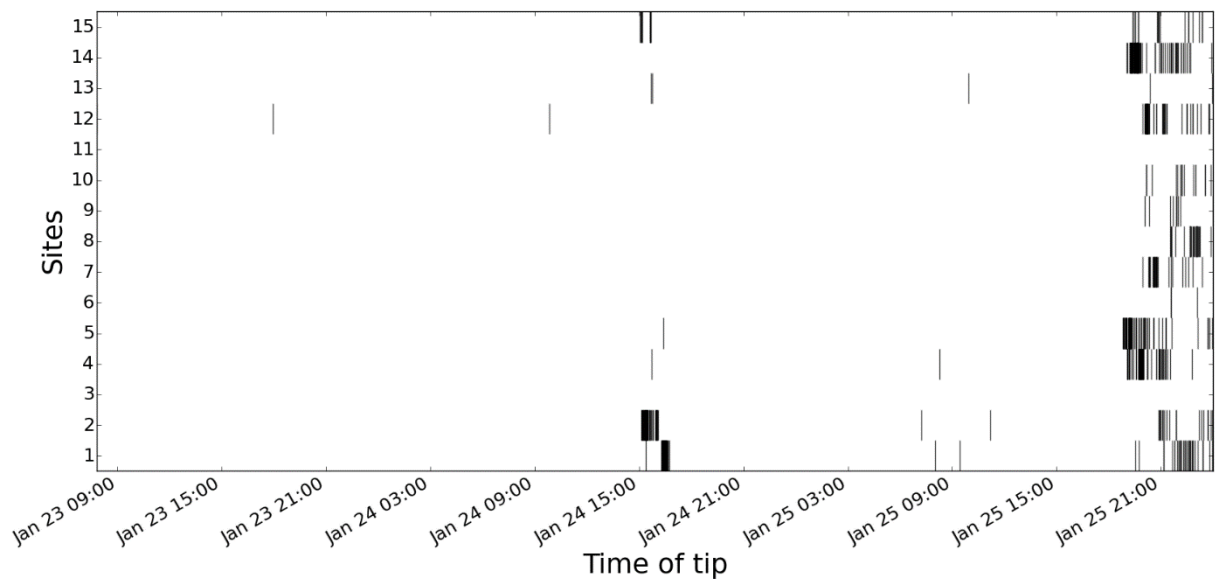


Figure 3-6: Rietfontein (Site 12) tip time series from 23 to 25 Jan 2015 (Individual tips are represented by a vertical tick).

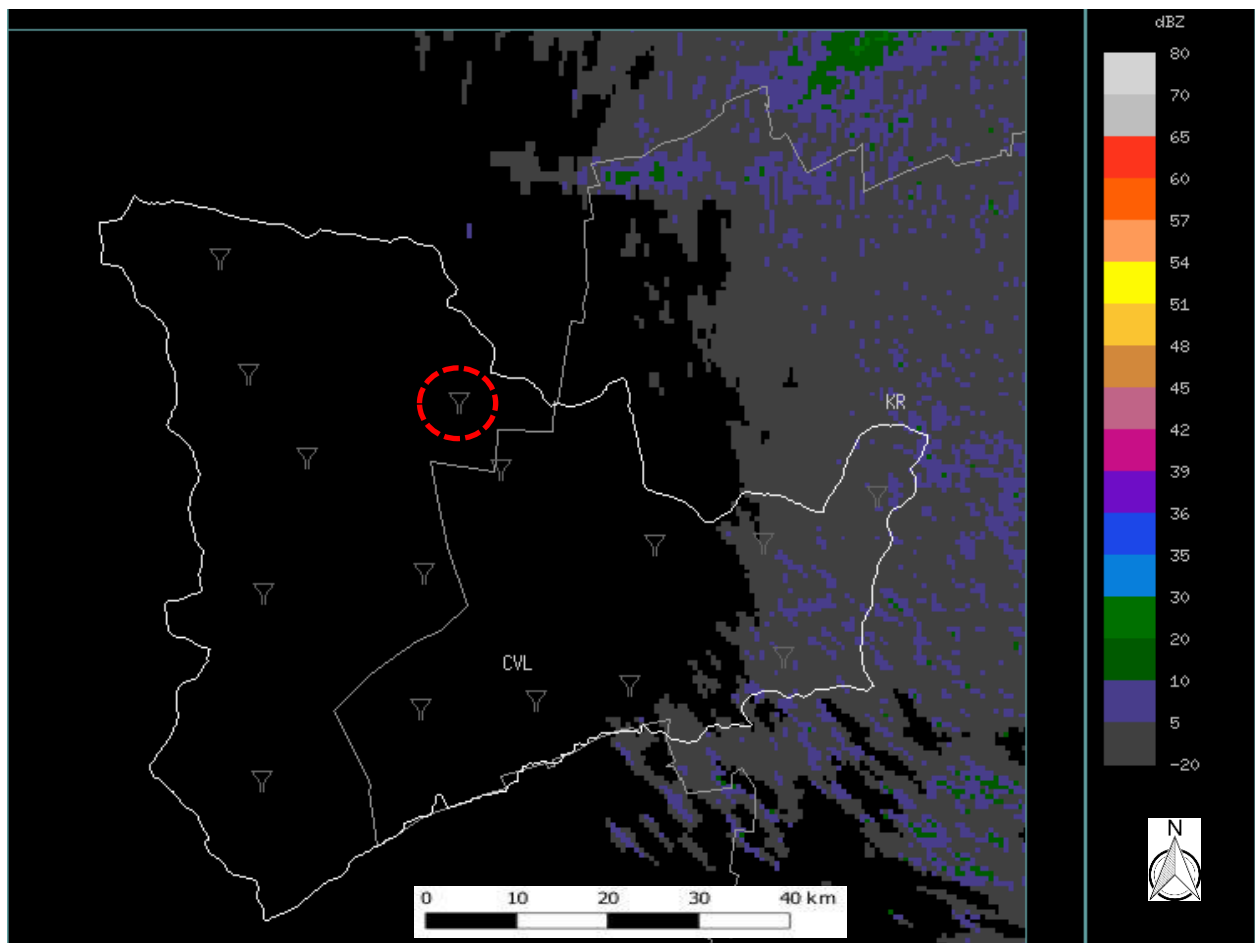


Figure 3-7: Irene radar image of the MRGN on 23 Jan 2015 at 15h56 with the location of the Rietfontein gauge (Site 12) circled in dashed red (Displayed with TITAN software).

3.4 Detecting partially blocked gauges

It is important to identify partially blocked gauges as such an occurrence can skew the temporal estimates made by a gauge, because the gauge is then recording rainfall at times where no rain is actually falling. The methods used in this study are aimed at identifying partially blocked gauges of the MRGN. When looking at each gauge of the MRGN individually, it will not be easily known if a gauge was completely blocked or out of order, unless a blockage was physically observed during gauge maintenance or if no tips were recorded for very long time periods when the other gauges did record rainfall such as in the case of the Welverdiend gauge between February 2015 and April 2015 where a spider's nest completely blocked the syphon of the gauge (see Figure 2-17). Thus, if there are no obvious explanations for long inter-tip gaps from a single gauge, it was concluded that it was a natural period of no rainfall. However, a partially blocked gauge could still be detected as there were anomalies seen in the data.

Partially blocked rain gauges will have rain accumulating in its funnel, before it flows through it and into the syphon and then the tipping buckets. Since the gauge is only partially blocked some water can still get through the blockage and into the buckets. The rate at which the water trickles through to the buckets depends on to which degree the funnel is blocked and also the amount of water accumulated in it. The rate that water moves through a partially blocked funnel is at its highest when the funnel is filled up, but as the water moves past the blockage through the funnel the rate of water reaching the buckets decreases because the water pressure above the blockage is reduced.

A characteristic example of a partially blocked gauge is illustrated by (Figure 3-8) , which shows the tips recorded by the Carletonville gauge (Site 10) which had a partial blockage, compared to the nearby correctly functioning Welverdiend gauge (Site 3) for the time frame of 15 to 17 November.

On the 15th of November a rainfall event occurred and ended just before 10 am on the morning of the 15th at the over the whole network, but at the Carletonville site that is just 12 km away from the Welverdiend site the gauge initially recorded much less tips than the rest and it also continued recording tips for another two days while the closeby Welverdiend gauge did not record any other tips afte the 15th of November.

It can also be seen on (Figure 3-8) that the inter-tip rain rates for the Carletonville gauge, were constantly increasing sequence of inter-tip rain rates. This is a common characteristic of a gauge that is partially blocked.

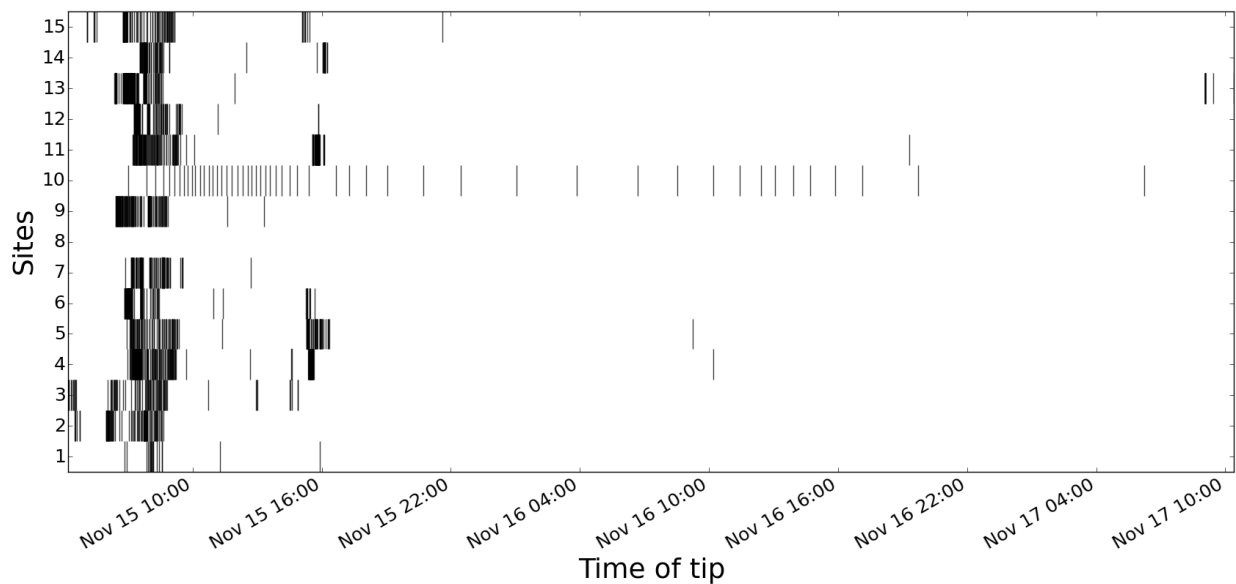


Figure 3-8: Carletonville (Site 10) tip time series of 15 to 17 Nov 2014 (Individual tips are represented by a vertical tick).

To verify that the Carletonville gauge (Site 10) was indeed partially blocked over the period of 15 to 17 November 2015, it is useful to look at some radar images for that particular time. From Figure 3-9 it is evident that there was indeed a rainfall event occurring over the Carletonville gauge (Site 10) on the 15th of November 2015 at 09h56. This corresponds with the first tips that was recorded just before 10h00 on the 15th of November 2015 by this gauge and can be seen on Figure 3-8. From there on this gauge keeps recording tips at regularly increasing intervals up until the 17th of November 2015 (Figure 3-8). However, when looking at the radar image of the area for the 16th of November 2015, it is clear that there was almost no rainfall event or precipitation around in the area, thus the Carletonville gauge (Site 10) must have been partially blocked, because it kept recording tips long after a rainfall event has passed.

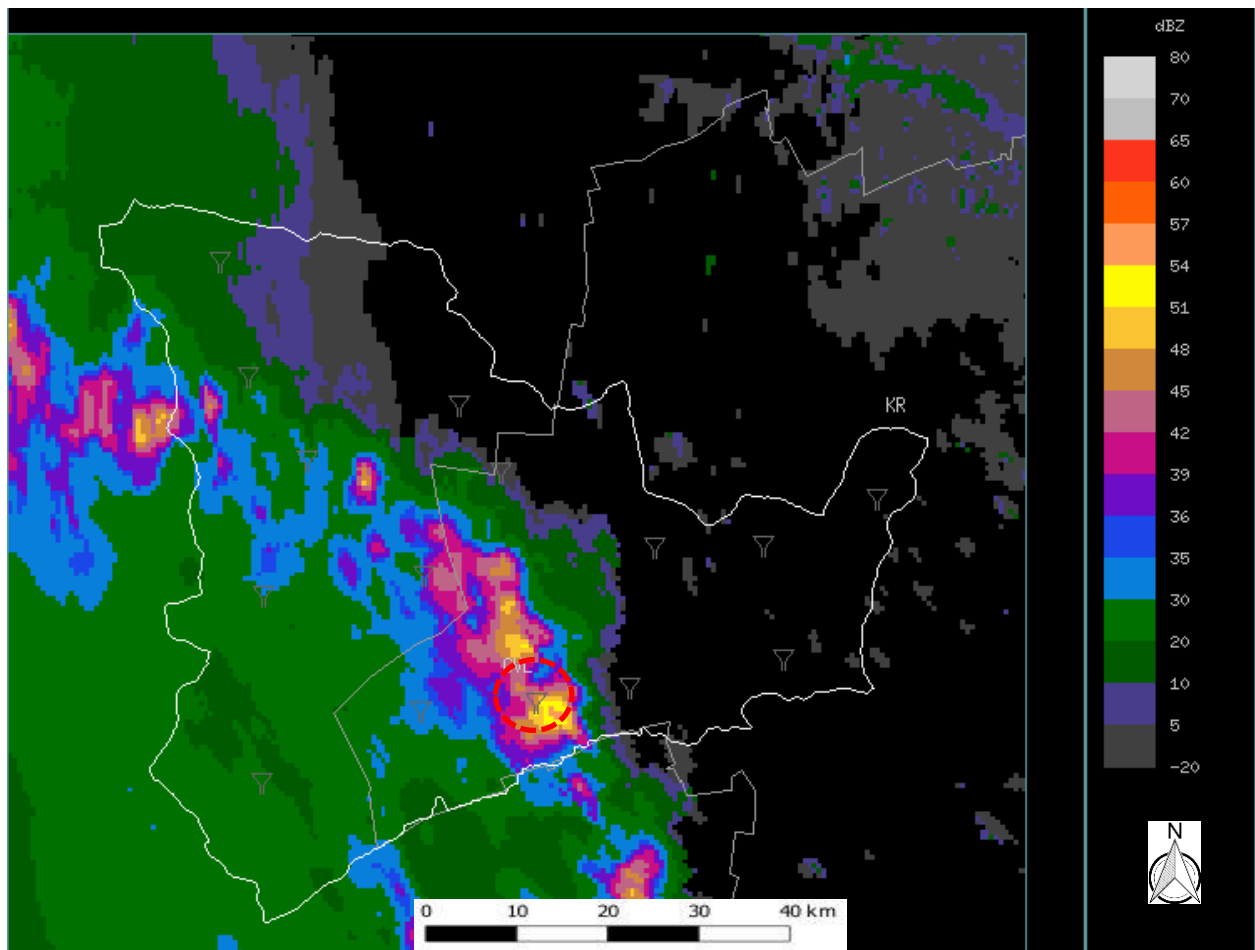


Figure 3-9: Irene radar image of the MRGN on 15 Nov 2014 at 09h56 with the location of the Carletonville gauge (Site 10) circled in dashed red (Displayed with TITAN software).

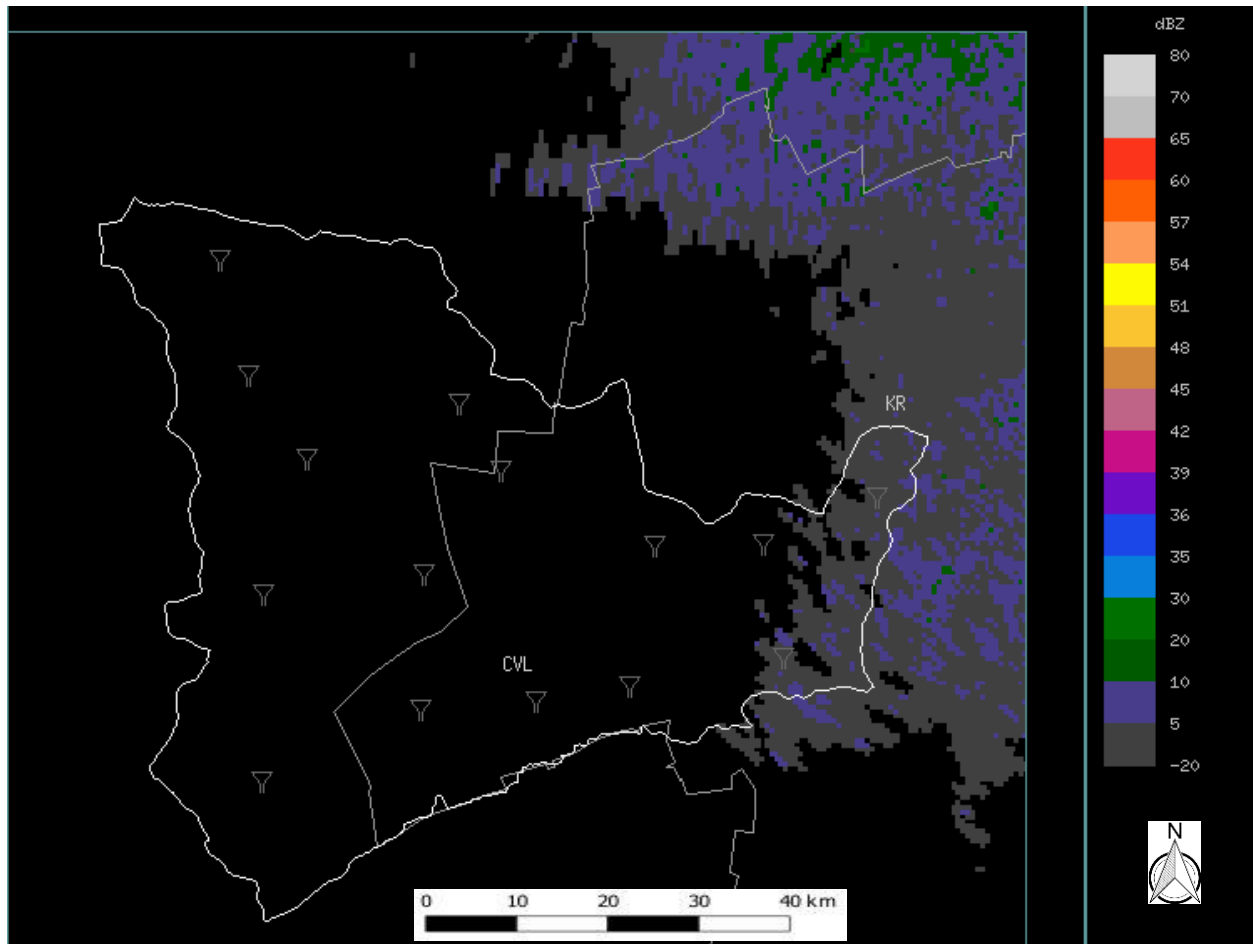


Figure 3-10: Irene radar image of the MRGN on 16 Nov 2014 at 15h32 with the location of the Carletonville gauge (Site 10) circled in dashed red (Displayed with TITAN software).

3.4.1 Increasing inter-tip rain rates

A partially blocked gauge will have inter-tip rain rates that are increasing: $r_i, r_{i+1}, r_{i+2}, \dots$ (Figure 3-11). However, a short sequence of gradually increasing inter-tip rain rates could also naturally occur during a rain event, thus a sequence of increasing inter-tip rain rates needs to be long to be significant. After all the faulty data was removed and inter-tip times of longer than 2 hours were removed, 24434 pairs of consecutive gaps R_r, R_{r+1} were found of which 49% had $R_{r+1} > R_r$ compared to 47% for $R_r > R_{r+1}$.

If the allocation of larger and smaller gaps between inter-tip rain rates were to be made at irregular intervals, the probability of a sequence of more than 10 incidents that are increasing would be $0.49^{11} = 0.0003$. This is equal to about one such sequence every 6 months where rain gauges experience rainfall similar to that in the MRGN area. The imbalance between 49 and 47% reflects the difference the rain rates have at the beginning and end of an event.

The restriction of inter-tip times longer than 2 hours reduces the possibility of long inter-tip gaps occurring by chance. Thus, restricting sequences to less than 2 hours, the change index δ_r is defined by

$$\delta_r = \begin{cases} 1 & \text{if } R_{r+1} > R_r, \\ 0 & \text{if } R_{r+1} = R_r, \\ -1 & \text{if } R_{r+1} < R_r, \end{cases} \quad (9)$$

(Upton and Rahimi, 2003)

Which suggest that a gauge may be partially blocked if an inter-tip sequence of 10 or more positive $\delta_r = R_{r+1} > R_r$, is observed.

For the MRGN data between November 2014 and June 2015 there were only one sequence of 11 or more positive δ_r values. A sequence of 13 increasing inter-tip rain rates was recorded by the Carletonville gauge on the 25th November 2014 (Figure 3-12).

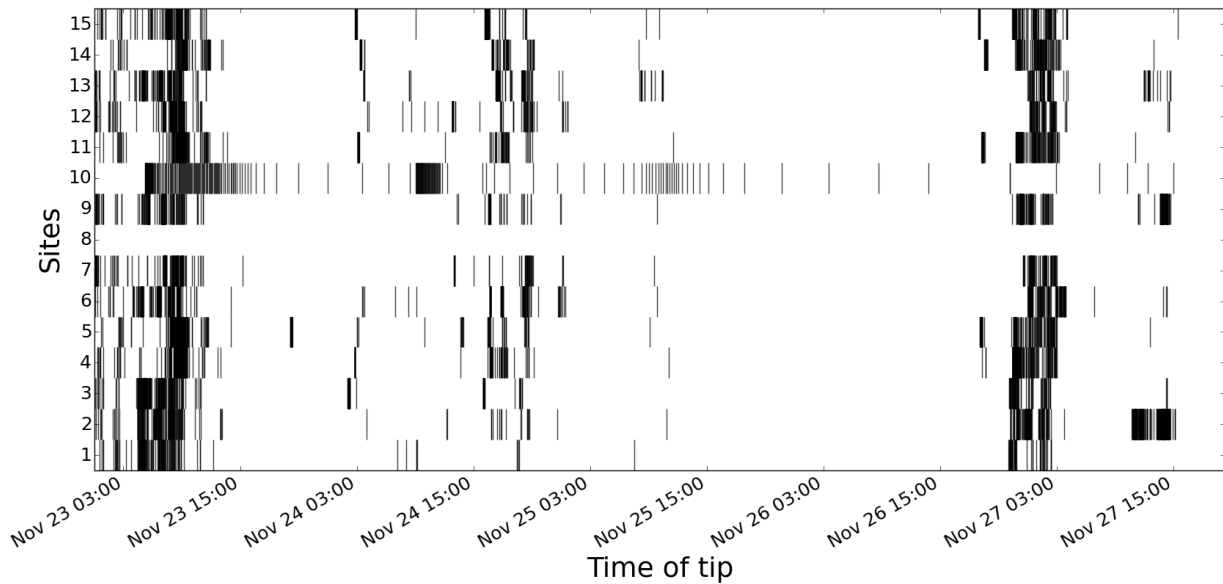


Figure 3-11: The increasing rain rate sequences of the Carletonville gauge on 25 November 2014.

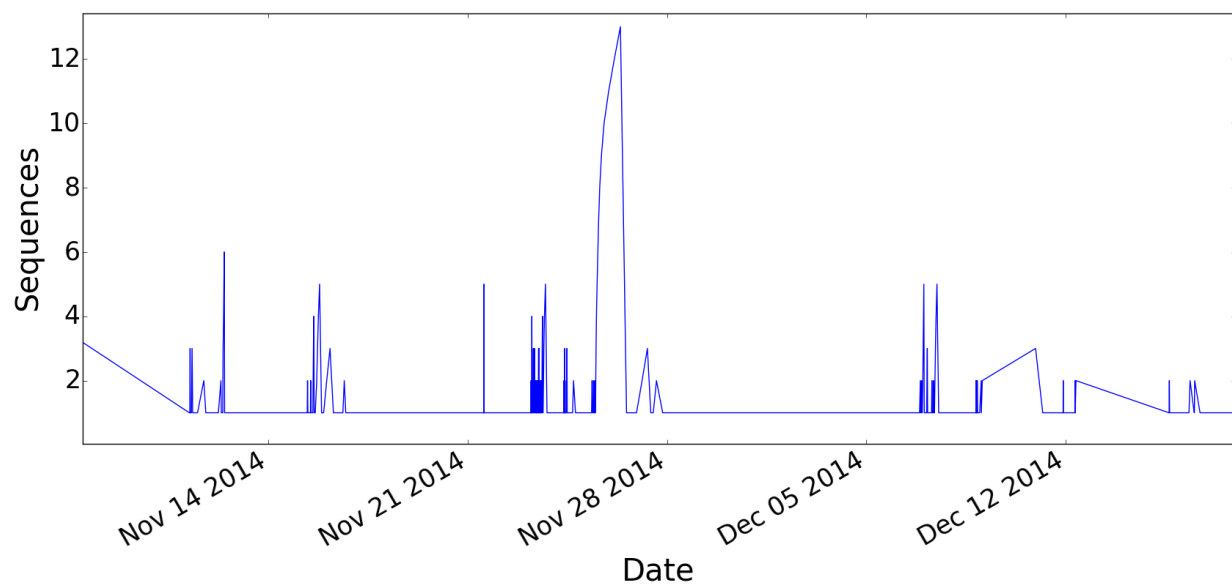


Figure 3-12: A sequence of more than 11 increasing rain rates identified at the Carletonville gauge.

CHAPTER 4 CHARACTERIZING THE SPATIAL VARIABILITY OF RAINFALL IN THE MOOI RIVER NETWORK

4.1 Climate of the network

To determine the climate characteristics of the MRGN, historical climate statistics was used from the WB40 report of the SA Weather Bureau, 1986 and the more recent climatic data (1984 to 2015) was obtained from SAWS 5 minute and daily reporting stations in and around the MRGN.

The climate for the MRGN is moderate with predominantly summer rainfall occurrence as shown in Figure 4-1 and in the climate statistics of the SAWS weather stations in Carletonville (Table 4-1), Potchefstroom (Table 4-3), Rustenburg (Table 4-4) and Krugersdorp (Table 4-2). 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 receives the least rain each year (Figure 4-1). SAWS have kept records of the South African climate since the early 1900's. The weather service maintains a climatological data set which has correlated all available data from the SAWS database into regions of similar rainfall. The MRGN falls within three of these climate regions (Region nr: 84, 85 and 74) as shown in Figure 4-2. These regions were delineated using the Thiessen's polygons interpolation technique. As seen in Figure 4-2, there are some artefacts on the boundaries of the regions that look unrealistic. 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 MRGN. As shown in Figure 4-3, there is a prominent negative east-west gradient in annual rainfall over the MRGN, 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 in the eastern part of the MRGN is 950 mm and the minimum is 420 mm. The inter-quartile 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 has a maximum annual rainfall 910 mm and a minimum of 380 mm. The inter-quartile range of annual rainfall for region 85, varies between 710 and 560 mm. Region 84 which is in 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 4-4 gives the cumulative frequency distribution of the total daily rainfall for all SAWS stations that fall within the three climate regions of the MRGN. The east-west gradient that is observed in Figure 4-3 can again be observed in Figure 4-4. It is

also evident that for 50% of rainfall events in these three regions, rainfall of less 7 mm are recorded where, 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 from Figure 4-4 that it is highly unlikely for rainfall of more than 10-20 mm to be recorded during most events over the three climatic regions.

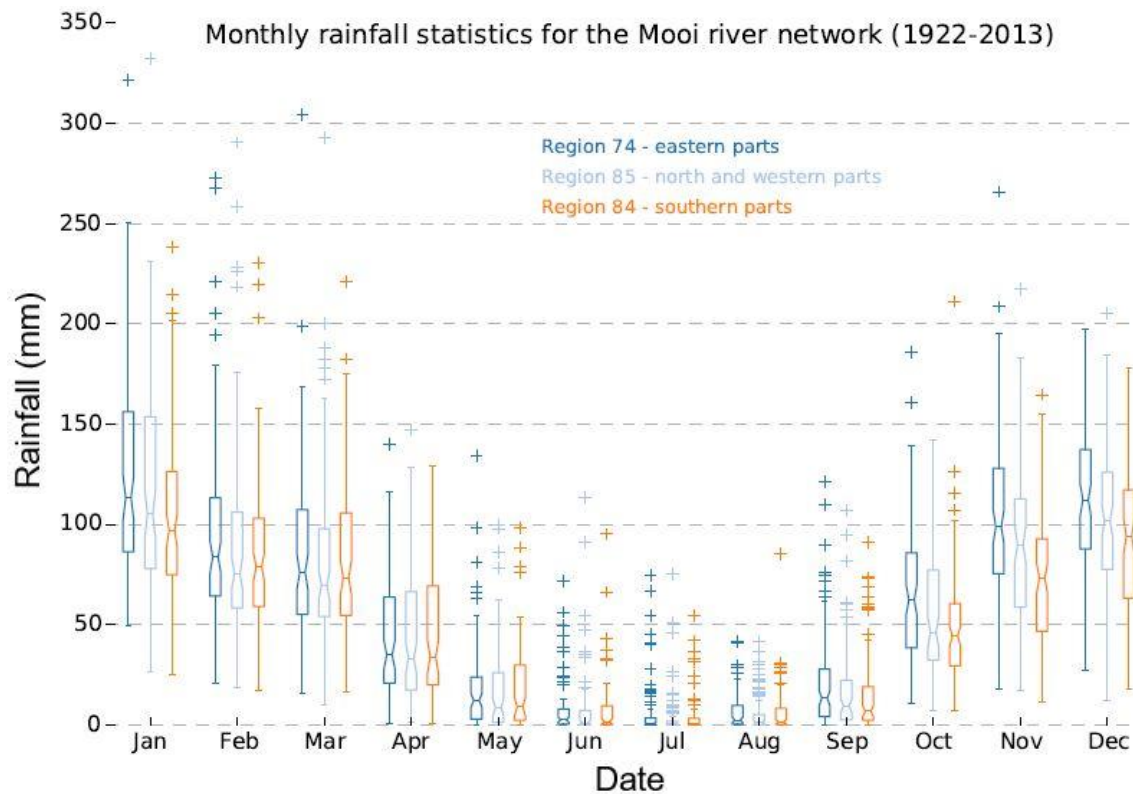


Figure 4-1: Monthly rainfall statistics for the southern (region 84), north and northwestern (region 85) and eastern (region 74) parts of the Mooi River network between 1920 and 2014 (S A WEATHER BUREAU (1986).

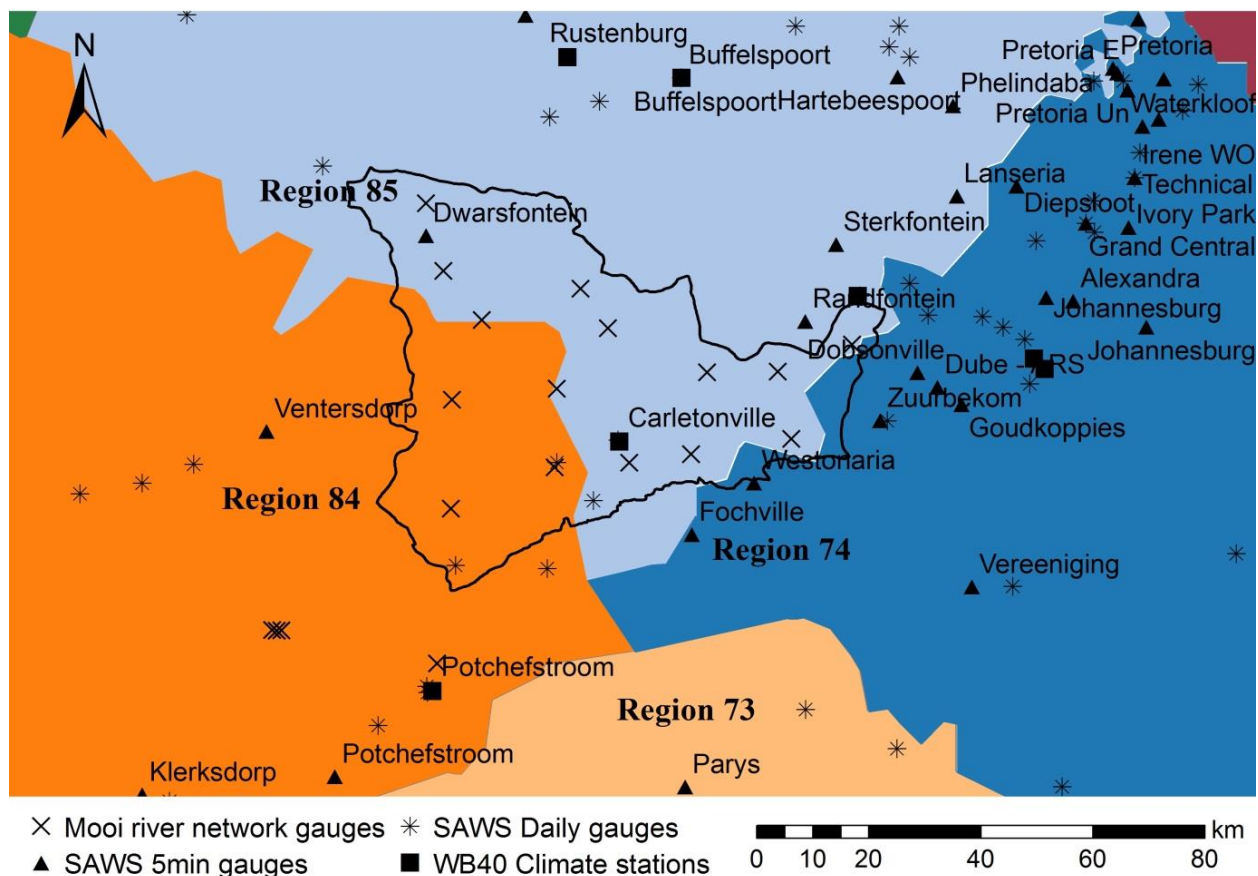


Figure 4-2: A map of the different climate regions for the Mooi River Network area as classified by SAWS. Map projection: WGS 84 / UTM zone 35S

Table 4-1: Rainfall climate statistics for the SAWS station at Carletonville (PUR), located at - 26.333333, 27.383333 for the period 1955-1984 (S A WEATHER BUREAU (1986).

Month	Average	Precipitation (mm)						Frequencies No of days with: Precipitation								Hail
		Max in 24h		Highest Monthly Max & Date		Lowest Monthly Min & Date		≥ 0.1mm			≥ 1.0mm			≥ 10mm		
		Σ	Date	Σ _x	Date	Σ _H	Date	Ave	Max	Min	Ave	Max	Min	Ave	Ave	
		P	30	30	Date	Σ _x	Date	Σ _H	Date	Ave	Max	Min	Ave	Max	Min	
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 4-2: Rainfall climate statistics for the SAWS station at Krugersdorp (MUN), located at -26.1, 27.7667 for the period 1951-1984 (S A WEATHER BUREAU (1986).

Month	Average	Precipitation (mm)						Frequencies No of days with: Precipitation						Hail		
		Max in 24h		Highest Monthly Max & Date		Lowest Monthly Min & Date		≥ 0.1mm			≥ 1.0mm				≥ 10mm	
		mm	Date	Σ _x	Date	Σ _H	Date	Ave	Max	Min	Ave	Max	Min		Ave	Ave
		P	34	34	34	34	34	34.0	34	34	34.0	34	34		34	34
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	

Table 4-3: Rainfall climate statistics for the SAWS station at Potchefstroom (AGR), located at -26.733333, 27.083333 for the period 1903-1984 (S A WEATHER BUREAU (1986).

Month	Average	Precipitation (mm)						Frequencies No of days with: Precipitation						Hail		
		Max in 24h		Highest Monthly Max & Date		Lowest Monthly Min & Date		≥ 0.1mm			≥ 1.0mm				≥ 10mm	
		mm	Date	Σ _x	Date	Σ _H	Date	Ave	Max	Min	Ave	Max	Min		Ave	Ave
		P	80	51		80		80		80.0	33	33	80.0		53	53
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	8.0	15	3	2.7	0.3	
4	46	83	1965/13	160	1971	0	1944	7.7	17	2	5.0	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	1.0	5	0	0.2	0.1	
7	8	41	1957/02	83	1918	0	1981	1.5	9	0	1.0	8	0	0.2	0.0	
8	9	39	1979/20	100	1922	0	1982	1.5	7	0	1.0	6	0	0.2	0.0	
9	18	53	1940/25	93	1940	0	1983	3.5	12	0	2.0	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	12.0	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			21.0	3.3	

Table 4-4: Rainfall climate statistics for the SAWS station at Rustenburg (AGR), located at - 25.71667, 27.3 for the period 1951-1984 (S A WEATHER BUREAU (1986)).

Month	Average	Precipitation (mm)						Frequencies No of days with: Precipitation							Hail	
		Max in 24h		Highest Monthly Max & Date		Lowest Monthly Min & Date		≥ 0.1mm			≥ 1.0mm			≥ 10mm		
		mm	Date	Σ _x	Date	Σ _H	Date	Ave	Max	Min	Ave	Max	Min	Ave		Ave
P	34	34		34		34		34.0	34	34	34.0	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	

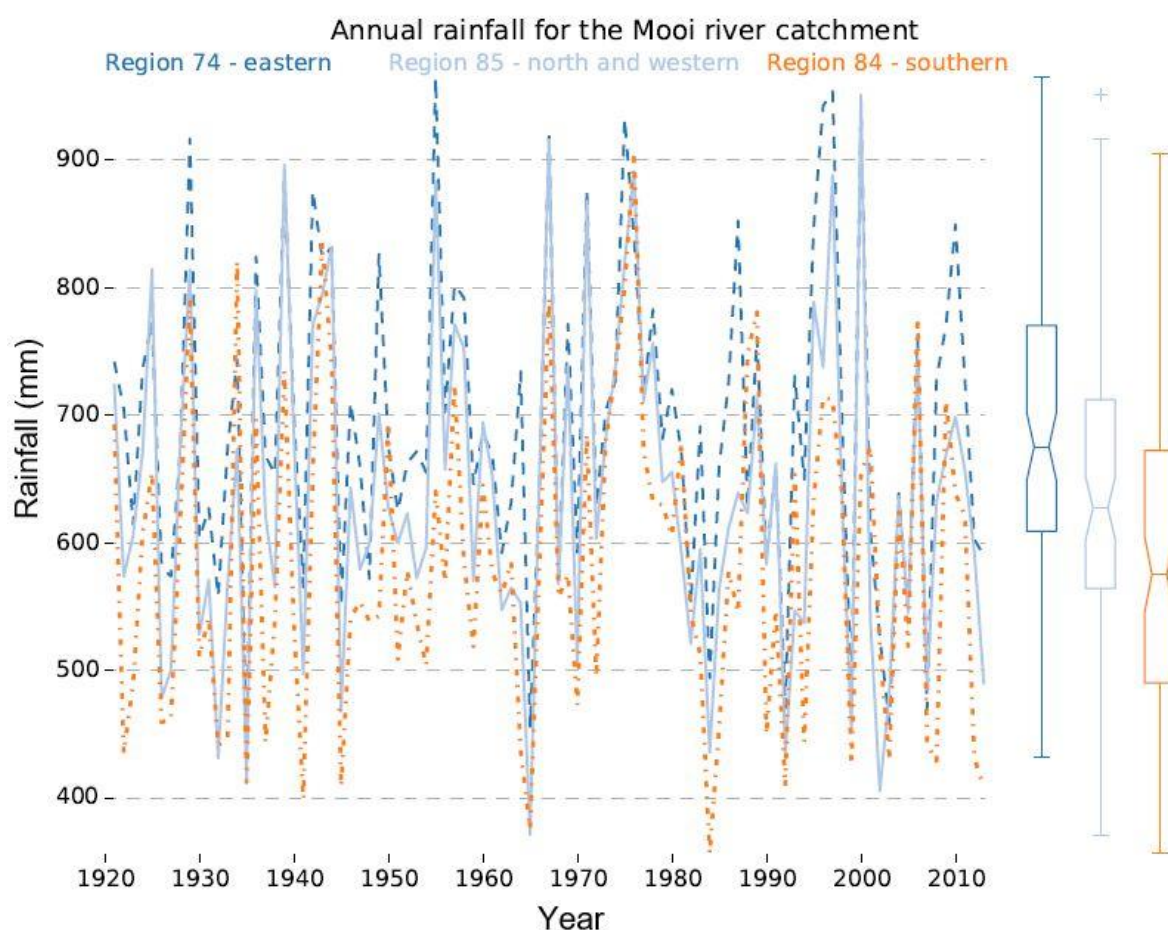


Figure 4-3: Annual rainfall for the southern (region 84), north and north-western (region 85) and eastern (region 74) parts of the Mooi River network between 1920 and 2014 (S A WEATHER BUREAU (1986)).

The median is the middle value when a data series is ranked from highest to lowest. It therefore designates a statistically expected value, with as many years having been wetter than the median as there are years having had less rain than the median value. Mean values are frequently inflated by a few heavy and extreme events, or outlier events, that may have occurred - a phenomenon which is especially prevalent in dry regions or in generally dry months. Under such rainfall regimes the mean is therefore not as representative of expected conditions as the median.

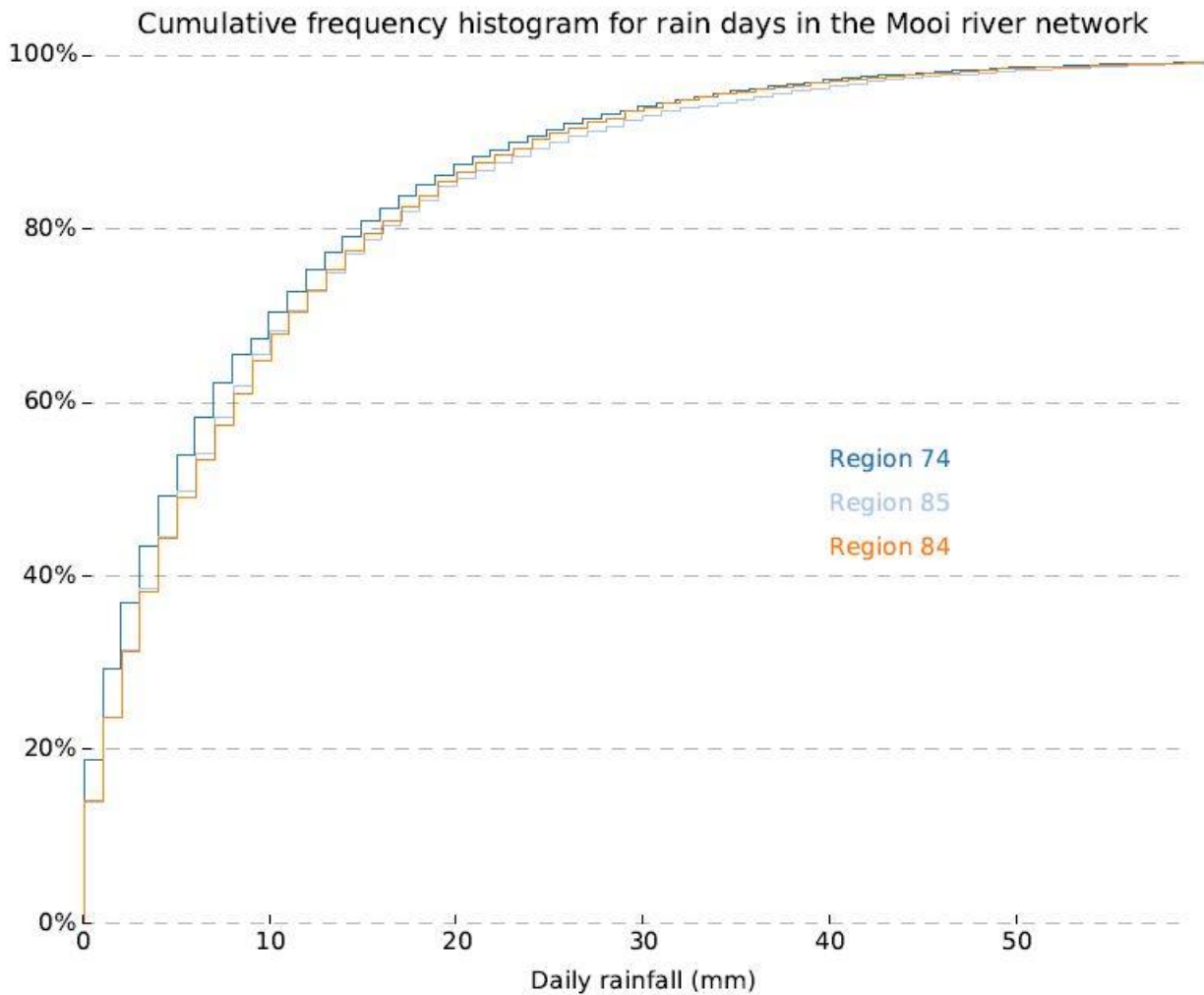


Figure 4-4: Cumulative frequency distribution of daily total rainfall for all SAWS stations in the southern (region 84), north and north-western (region 85) and eastern (region 74) parts of the Mooi River network between 1961 and 2014 (S A WEATHER BUREAU (1986).

4.2 Rainfall during the 2014/2015 season

The average rainfall for the MRGN during the 2014/2015 rainfall season was slightly less than the historical average for the region over the same period of time (Figure 4-5). The historical rainfall average for the region was determined with the same data that was used in section 4.1 of chapter 4 in this document. As shown in Figure 4-5 the average rainfall for November 2014 was almost 20 mm more than the historical average for the same month, thus it can be said that the MRGN had an above average amount of rainfall during November 2014. However, after November 2015 the picture changed quite a bit. Every other month of the study period had below average rainfall. The biggest deviation occurred in February 2015 where the MRGN recorded almost 50 mm of rainfall less than the historical average for the same month. The same also goes for rainfall in May 2015. Historically the month of May receives about 20 mm of rainfall in the MRGN. However, in the 2015 season no rain was recorded at all in the MRGN during the month of May.

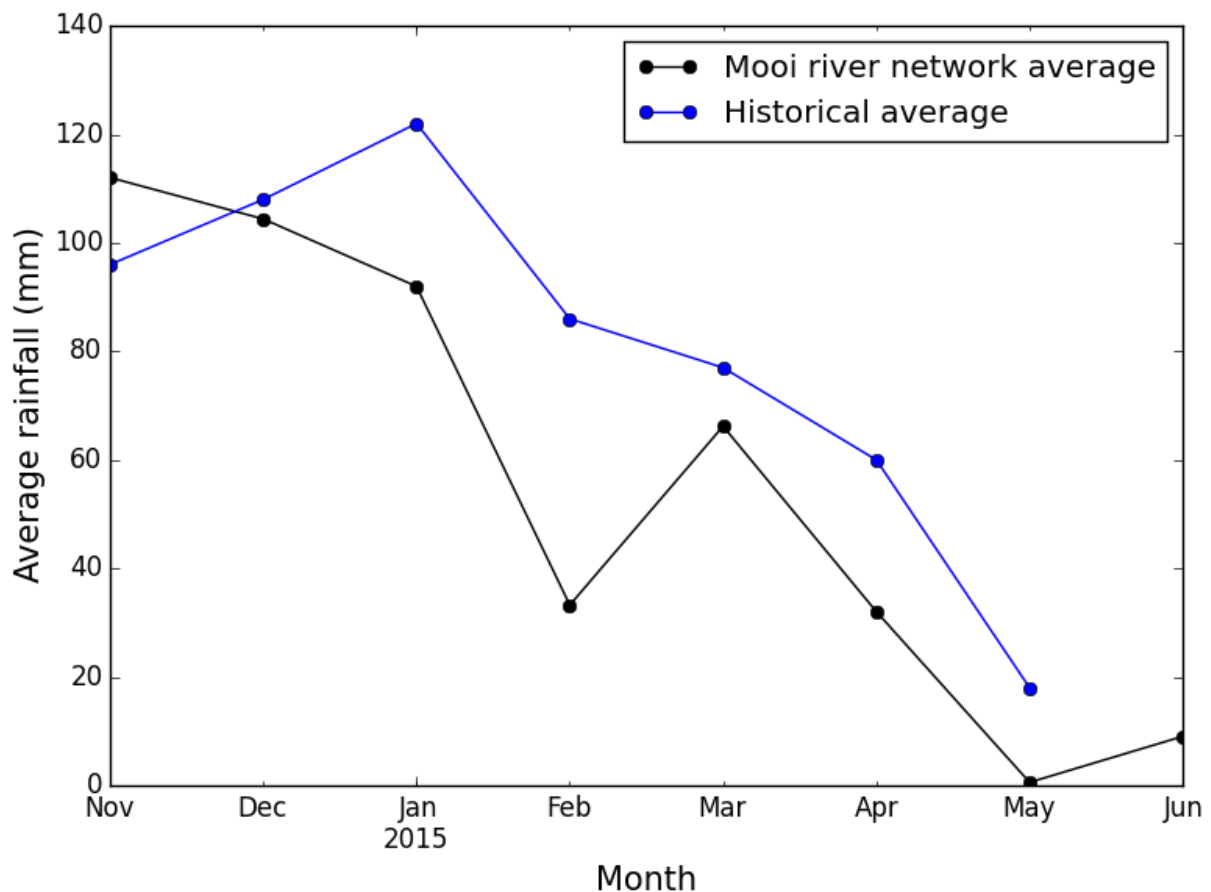


Figure 4-5: The average monthly rainfall of the MRGN for the study period of November 2014 to June 2015 and the historical average for the same period.

Looking at the spatial distribution of the total measured rainfall over the MRGN between 2014-12-10 and 2015-01-11 (Figure 4-6), it was evident that the south west corner of the catchment received the least amount of rainfall. The fact that the south west corner of the catchment received less rainfall than the rest of the catchment, also shown previously (Figure 4-3 and Figure 4-4). However, it is important to note that the whole MRGN catchment received below average rainfall during this period of time (Figure 4-5).

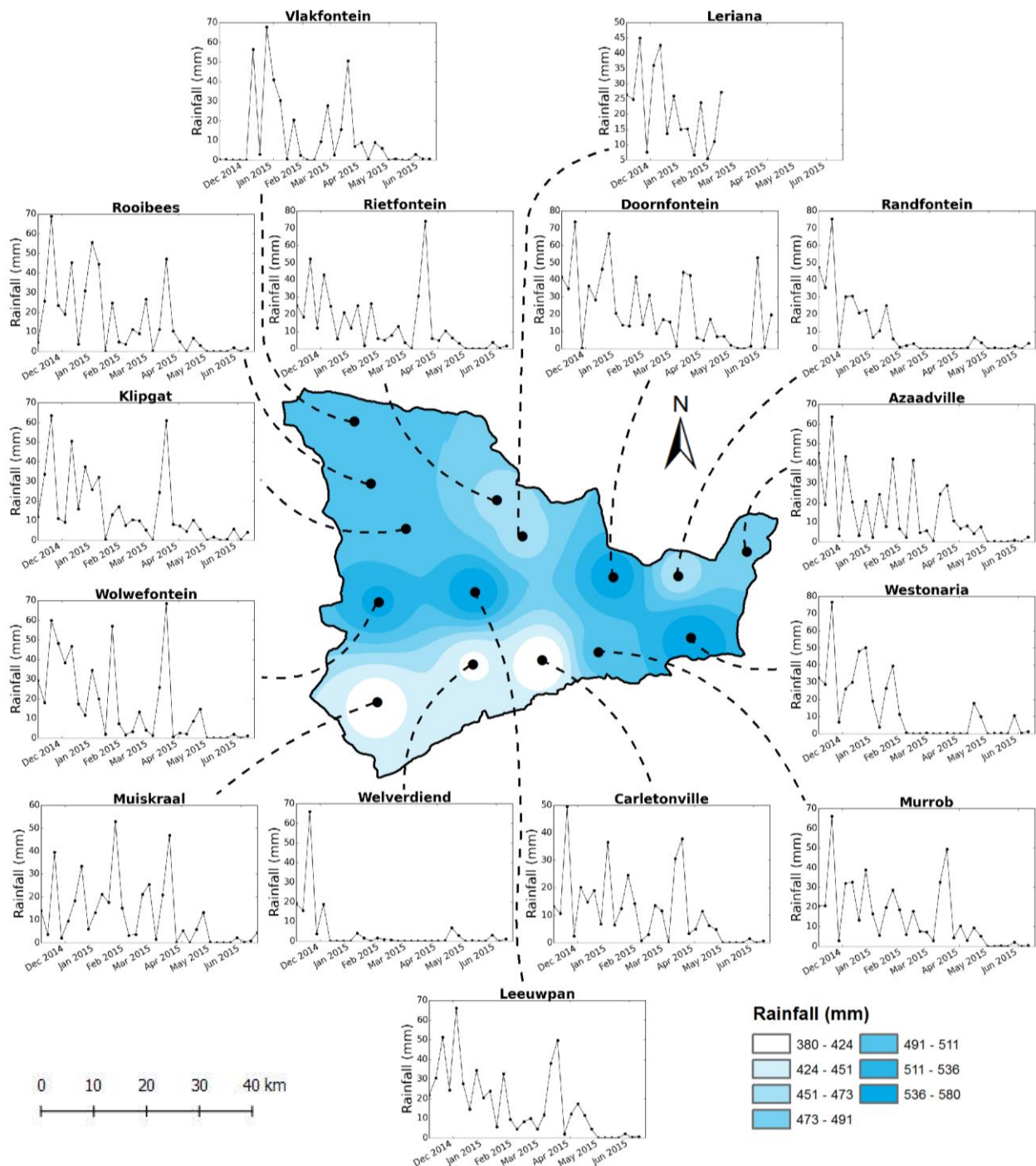


Figure 4-6: Total rainfall for MRGN between 2014-12-10 and 2015-01-11, with monthly totals for each gauge in graph format. Map projection: WGS 84 / UTM zone 35S

When each rain gauge of the MRGN is looked at individually (Graphs shown in Figure 4-6), it is evident that most gauges received the most rainfall during December 2014 and the least amount of rainfall during June 2015. This correlates well with the historical monthly rainfall totals also showing that December receives the most rainfall and June receiving the least (Figure 4-1).

4.3 The spatial and temporal variability of rainfall for the MRGN

There is considerable spatial and temporal variation of rainfall measured between the rain gauges of the MRGN (Figure 4-7). The spatial correlation between the rain gauges of the MRGN improves as the accumulation time increases. The correlations of one-minute rainfall over the network are 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. Thus it is evident that the MRGN is dense enough in space to provide rainfall data for water management and agricultural practises, 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 min averaging periods.

Results of the daily and 12 hourly rainfall analysis show that there was considerable spatial variation in rainfall. It was, however, evident that over longer temporal scales there was less spatial variation (Figure 4-7). The daily rainfall correlation varies less over distance than the 12 hourly correlations. For the daily analysis in Figure 4-7, correlations range between 0.9 and 0.4 for separation distance < 60 km. The 12 hourly analysis (Figure 4-7) correlations exhibited much stronger downward curve with weaker correlation at longer distances between 40 km and 80 km as opposed to the daily analysis.

(Mzezewa et al., 2010) identified the probability distribution of rainfall data. This was done by fitting the observed distributions to a theoretical probability distribution by comparing frequencies observed in the data with the expected frequencies of the theoretical distribution since certain types of variables follow specific distributions. Preliminary data normality was tested using skewness and kurtosis coefficients. Probability plots were also constructed to evaluate the probability distributions. Goodness-of-fit test were based on the Anderson-Darling test. This test statistically measures how well the data follow a particular distribution. The better the distribution is fitted to the data the smaller the statistic is.

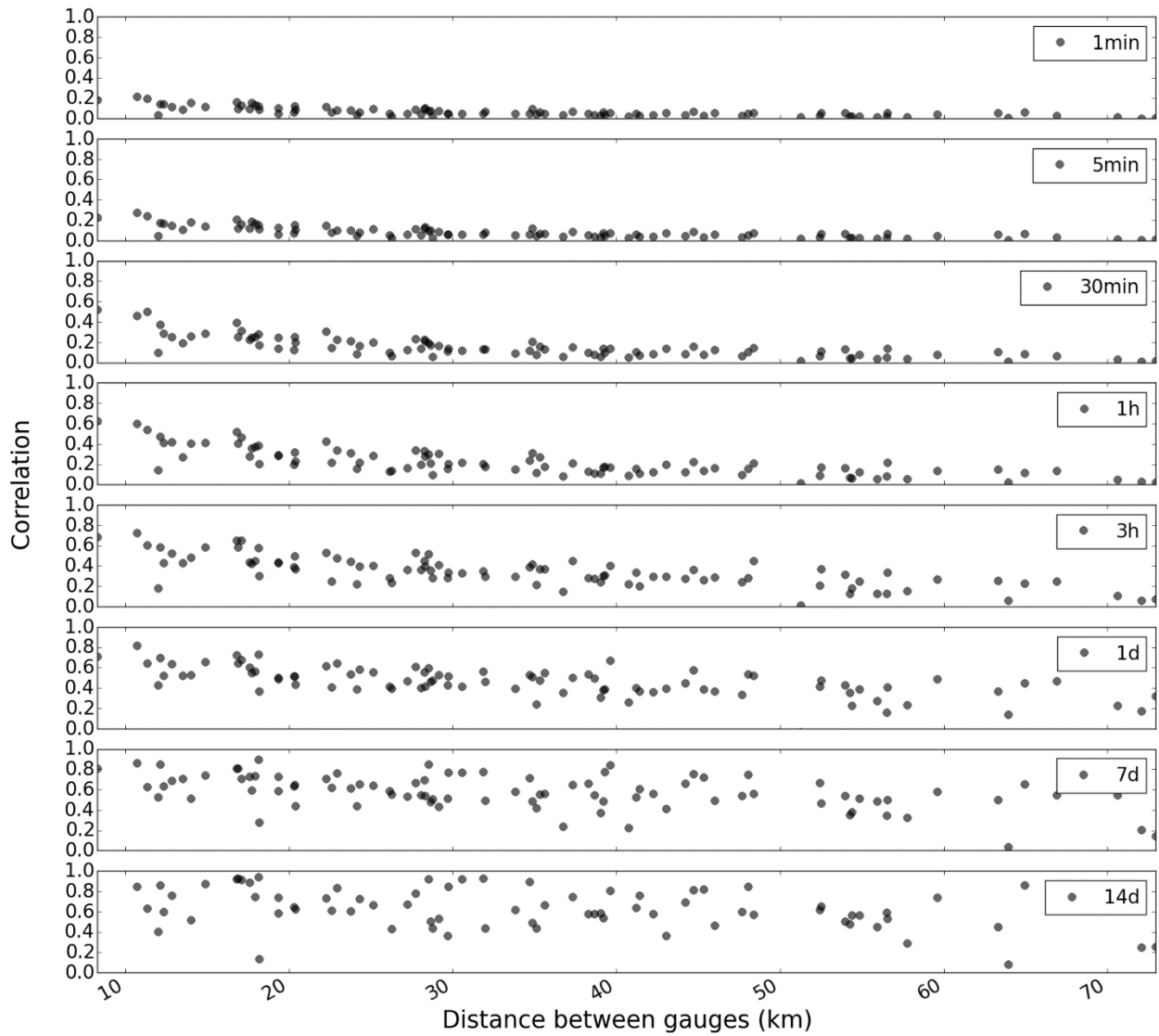


Figure 4-7: The spatial correlation between rain gauges in the MRGN for different time resolutions ranging from 1 minute to 14 days of rainfall accumulation periods.

The correlation distance is the measure of spatial variability of rainfall and is one of the key parameters in designing a gauge network. Correlation distances are sensitive to the integration period, rain/no-rain threshold, rainfall characteristics and the size and gauge density of the domain (Tokay et al., 2014).

The dominant storm types during the rainfall season of this area were convective and stratiform rainfall. There was a notable difference in the level of spatial variation of rainfall exhibited for each of these 2 storm types. For example, during convective storms there was a high spatial variation of rainfall, whereas for stratiform storm types rainfall was less variable in space.

CHAPTER 5 OPTIMIZING THE MOOI RIVER RAIN GAUGE NETWORK (MRGN)

5.1 Evaluation and augmentation of the MRGN

Rain gauge networks consist of a number of rain gauges that are spread out over a particular area of interest. Important considerations to take note of when designing or evaluating a network is the density and location of rain gauges in the network. The optimal density of a network depends on the purpose that the network is designed for and the characteristics of the climate over the area of interest. If a network is designed for water resource management, data is needed of the monthly, seasonal and annual rainfall, whereas a network designed for radar calibration or flood forecasting and mitigation will need rainfall data at a much finer temporal resolution such as hourly or even smaller rainfall durations. Rainfall at small time scales (such as hourly or event rainfall) exhibits higher spatial variability than rainfall at longer time scales, which tend to be stochastically less variable in space and has higher spatial correlation. Therefore, it can be said that for water resource management, where long duration rainfall data is needed a low density network will be adequate in capturing the spatial variability of rainfall, whereas for radar calibration or flood forecasting and mitigation a higher density network will be needed.

When evaluating a rain gauge network, an important consideration is how to quantify the performance of the network. To measure network performance, the accuracy associated with estimates of point rainfalls across the study area must be determined. The accuracy should both indicate the absolute error as well as the error variance, since errors go hand in hand with the variability of rainfall, and the variability of rainfall varies between on event and another. Thus, if only unbiased estimators such as a radar field or interpolation of point rainfalls are considered, the estimation accuracy can then be determined by the variance of estimation error.

Spatial interpolation algorithms such as ordinary kriging are just one of the many geostatistical methods used in network evaluation, which can give unbiased estimates' with minimal error variance. Ordinary kriging is the most popular method due to its computational simplicity and data availability in most applications (Gentile et al, 2012; Goovaerts, 2000). Thus kriging variance has been commonly used as a tool in rain gauge network design and evaluation.

Ordinary kriging is used to determine the variance of the estimation error by each rain gauge in the network. Thus, the focus is placed on the estimation accuracy of areal average rainfall by the network and on estimation accuracy for point rainfall across the study area. A good rain gauge network should yield acceptable accuracy for most points within the study area.

5.1.1 Interpolation of rainfall totals in the MRGN

To interpolate rainfall totals using ordinary kriging, a variogram was constructed from the point values that was observed at each rain gauge site. Then a variogram model was fitted to the scattered observation points. Variogram modelling is similar to fitting the least-square line in regression analysis. The most common variogram models are spherical, linear, exponential, experimental and Gaussian (Ver Hoef & Barry, 1998; Gringarten & Deutsch, 2001; Mair and Fares, 2011; Putthividhya and Tanaka, 2012).

The data used in this section for interpolation of rainfall totals for each of the 15 gauges in the MRGN between 2014-12-10 and 2015-01-11 are given by Table 5-1. The time frame of 2014-12-10 to 2015-01-11 was chosen as it is one of the only times during the study period which all 15 gauges was online continuously and working in good stead.

Table 5-1: The cumulative rainfall amounts for the gauges of the MRGN between 2014-12-10 and 2015-01-11.

Site	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Rainfall (mm)	59.22	155.42	104.22	150.41	145.02	122.60	103.81	111.57	128.21	75.82	159.21	107.61	120.62	131.00	110.01

For this study the exponential, Gaussian and spherical models (Figure 5-1, Figure 5-2, Figure 5-3), were used and each model's variogram parameters (sill, range and nugget) were calculated, as well as two error statistics (namely: mean error and root-mean-square standardised error). Using the error statistics is helpful to determine which model is best for calculating the unknown values of the rainfall field (i.e. the interpolated values between known rain gauge observations). A model was considered good at predicting unknown values if the mean error is close to zero and the root-mean-square standardised error is close to 1.

The two error statistics were calculated as follows: $\hat{Z}(x_i)$ is the unknown rainfall value as predicted by the kriging interpolation method, $Z(x_i)$ is the observed rainfall value at the gauge site x_i , and $\hat{\sigma}(x_i)$ is the standard error for site x_i .

Then the mean error (m) can be calculated with:

$$m = \sqrt{\frac{\sum_{i=1}^n (\hat{Z}(x_o) - Z(x_o))^2}{n}}$$

And the root-mean-square standardised error (η) can be calculated with:

$$\eta = \sqrt{\frac{\sum_{i=1}^n [(\hat{Z}(x_o) - Z(x_o))/\hat{\sigma}(x_i)]^2}{n}}$$

Where n is the number of values in the dataset.

As shown in Table 5-2, the nugget and range parameters for the three variogram models are exactly the same and the sill parameters for the spherical and Gaussian model are approximately the same. It is however evident that the sill parameter for the exponential model is different than the res. When looking at the error statistics it is also evident that the exponential model has a mean error closer to zero than the other two models and the root-mean-square standardised error of the exponential model is the closest to one out of the 3 models that were considered. Therefore, the exponential model was chosen to interpolate rainfall data in this study as it will give the most reasonable map prediction.

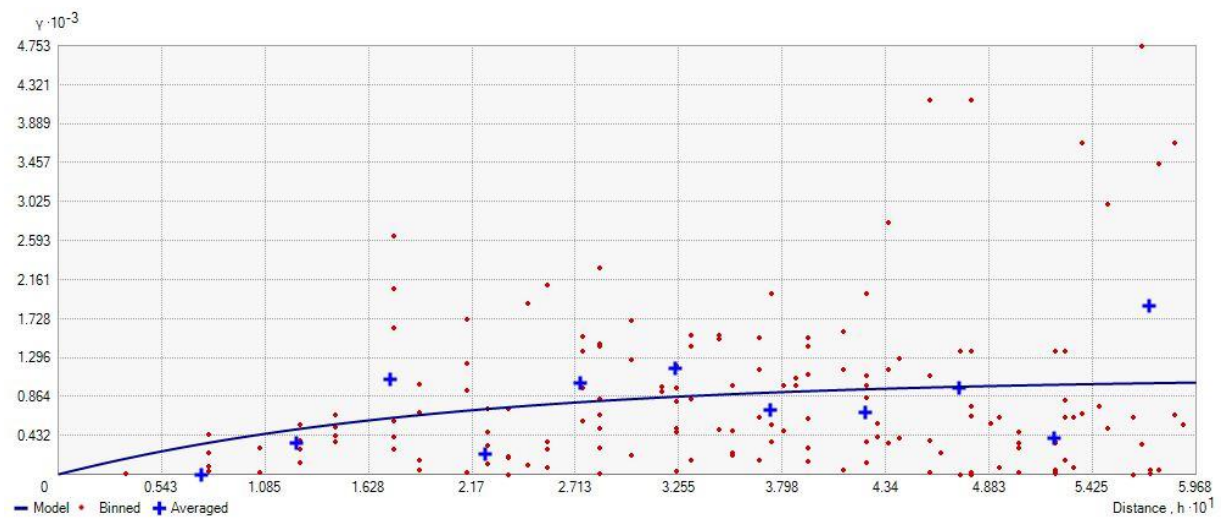


Figure 5-1: Exponential variogram model.

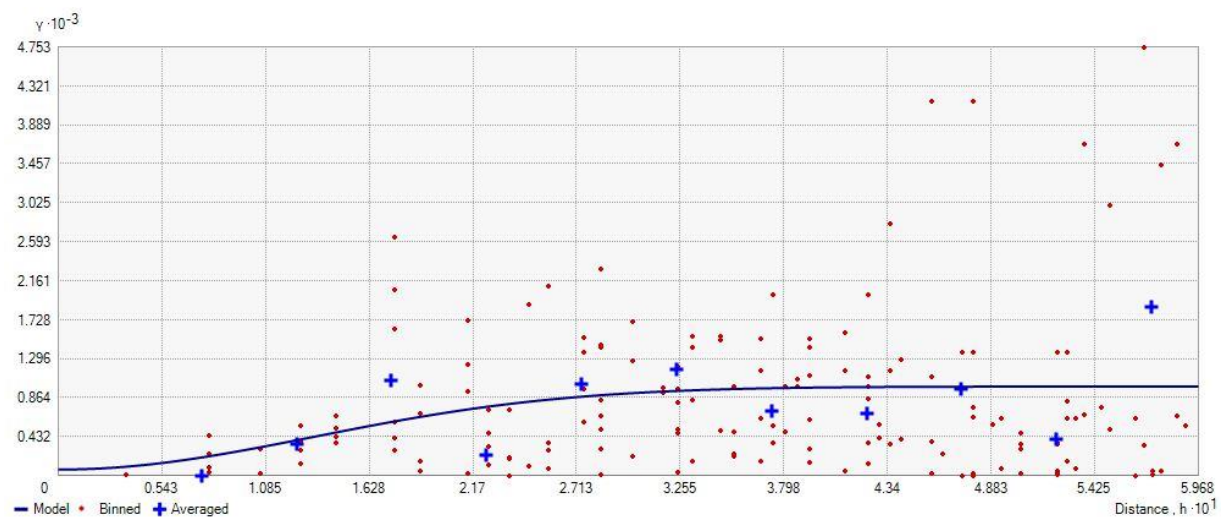


Figure 5-2: Gaussian variogram model.

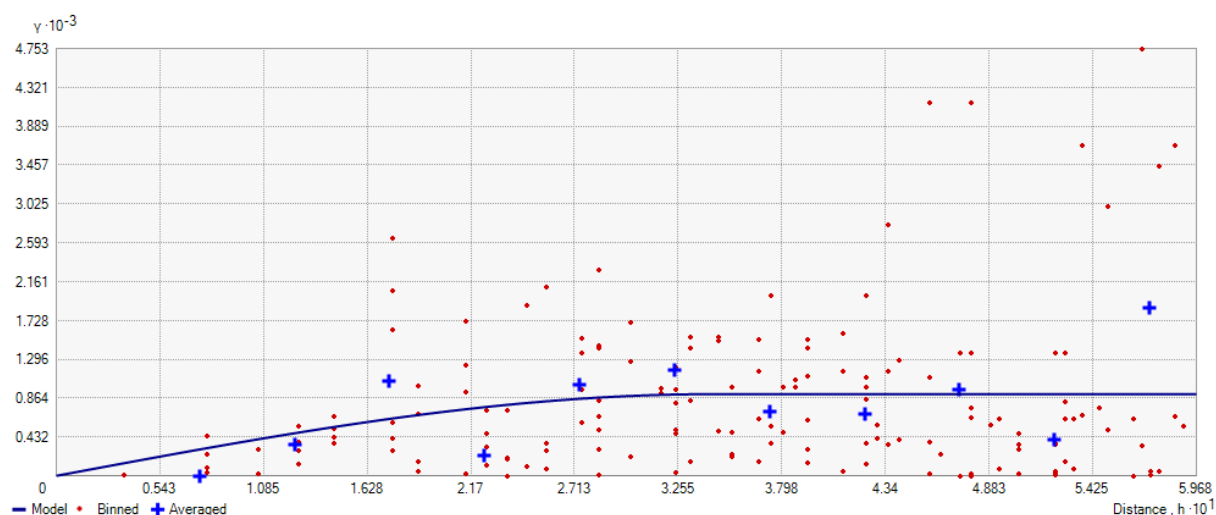


Figure 5-3: Spherical variogram model.

Table 5-2: Experimental and fitted variogram parameters and error statistics for rainfall in the MRGN during 2014-12-10 and 2015-01-11

Model variogram	Sill	Range	Nugget	m	η
Exponential	1071.4	327016	0	1.63	1.01
Gaussian	920.6	327016	0	2.28	1.19
Spherical	908.3	327016	0	2.34	1.01

The exponential variogram model was used to interpolate rainfall data from the MRGN (Table 5-1) using the kriging interpolation method and the resulting rainfall field can be seen in Figure 5-4. This map of the rainfall field over the MRGN indicates that cumulative rainfall totals for the period of 2014-12-10 to 2015-01-11 decreased from east to west and from north to south. This finding corresponds well with the finding made in chapter 4 of this document, where it was determined from the climatic records for the area that rainfall does decrease from east to west over the Mooi river catchment.

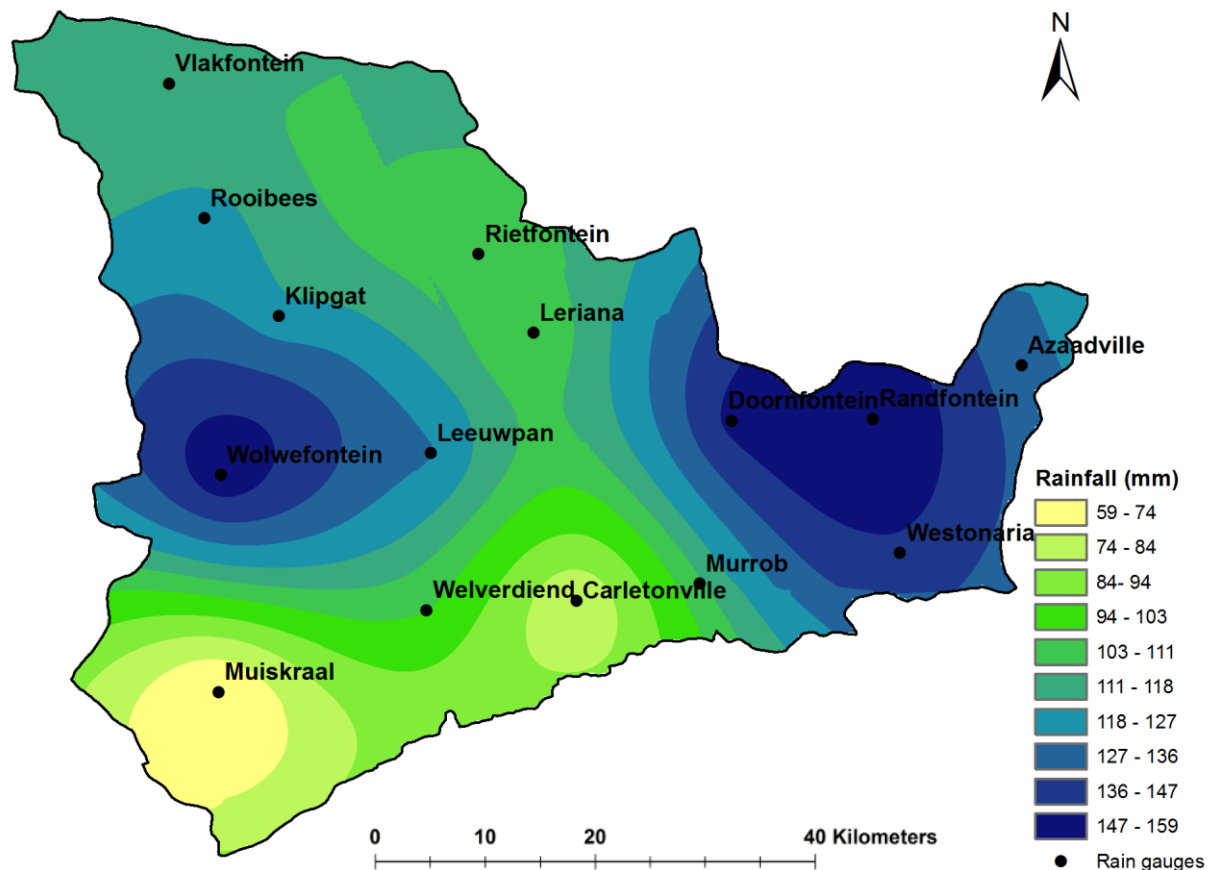


Figure 5-4: The cumulative rainfall field in MRGN between 2014-12-10 and 2015-01-11 created by using an exponential model in the kriging interpolation method. Map projection: WGS 84 / UTM zone 35S

5.1.2 Network performance evaluation based on the percentage of area with acceptable accuracy

The goal for optimum rain gauge network design is to obtain data out of the network that is representative of the spatial distribution of rainfall over the study area with enough accuracy for practical and operational situations.

To determine the optimal amount of rain gauges to be deployed over the MRGN the kriging variance of estimation error was used to identify areas that are not sufficiently represented by rain gauges. In this study the threshold for variance of estimation error is 10%. Thus, any areas in the MRGN that has a kriging estimation error of more than 10%, need additional rain gauges in order to effectively measure rainfall within the MRGN (Figure 5-5).

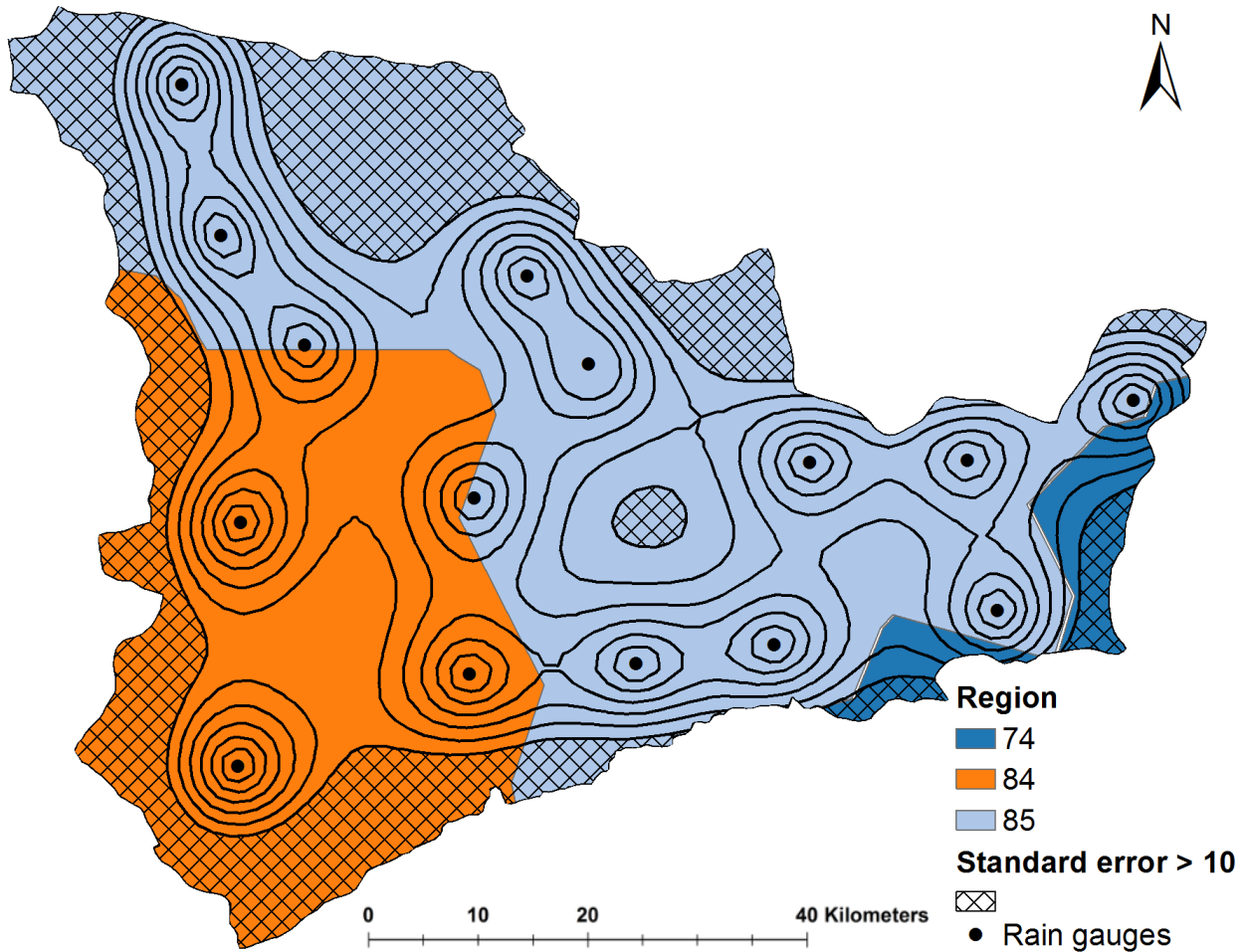


Figure 5-5: Contour map of kriging variance for total rainfall in MRGN between 2014-12-10 and 2015-01-11. Map projection: WGS 84 / UTM zone 35S

As indicated by Figure 5-5, there quite a few areas within the MRGN catchment area where there is not sufficient representation by rain gauges, especially at the edges of the catchment.

To determine the exact number of gauges that is needed in the MRGN, the following equation was used:

$$N = \left(\frac{C_v}{\varepsilon} \right)^2 \quad (10)$$

N represents the optimal number of gauges for the network and C_v is the coefficient of variation in rainfall estimates over the whole network of current rain gauges. And lastly ε is the degree of variance estimation error from the mean that is permissible for this network of gauges, which is 10% as previously mentioned.

To determine the coefficient of variation, the following equation was used:

$$\text{coeff of variation} = \frac{\text{std deviation}}{\text{mean}} \quad (11)$$

Thus:

$$C_v = \frac{0.79}{1.49} = 53$$

Thus, the optimal amount of rain gauges in the MRGN is:

$$N = \left(\frac{C_v}{\varepsilon} \right)^2 \rightarrow N = \left(\frac{53}{10} \right)^2 = 28.09 \approx 28$$

Therefore, it was determined that the optimum number of rain gauges for the MRGN should be 28. Currently there are 15 gauges in the MRGN, thus there are 13 additional gauges needed.

Once the amount of rain gauges is known for an optimal design of the MRGM, the last step is to determine how to distribute the additional gauges across the catchment of the MRGN. It was decided that the additional gauges should be distributed over the network according to the three climatic zones that are found over the catchment of the MRGN.

There are three climatic zones within the MRGN catchment (Figure 5-5). To determine how many additional gauge should be placed in each climate zone, the area of each zone within the catchment was converted to a decimal and then multiplied with the optimal amount of gauges for the network. This gave an estimate of 1 additional rain gauge for climate region 74, 7 additional gauges for region 84 and 5 additional gauges for region 85 (Table 5-3).

Table 5-3: The amount of additional rain gauges that is needed in the MRGN during 2014-12-10 and 2015-01-11.

Climate Region	74	84	85	Total
Area (km ²)	151	1148	1995	3294
Area as decimal	0.05	0.35	0.61	1
N' Area in decimal (N=28)	1.4	9.8	17.08	
Rounded as	1	10	17	30
Existing rain gauges	0	3	12	15
Additional rain gauges	1	7	5	13

The placement of additional gauges to the existing network was then evenly distributed over the areas within the three climate regions where the standard error was more than 10% (Figure 5-6).

Each of the additional gauges was placed through a trial and error procedure, where areas with the least kriging variance error was favoured as well as the accessibility to each additional gauge location and cost of installation.

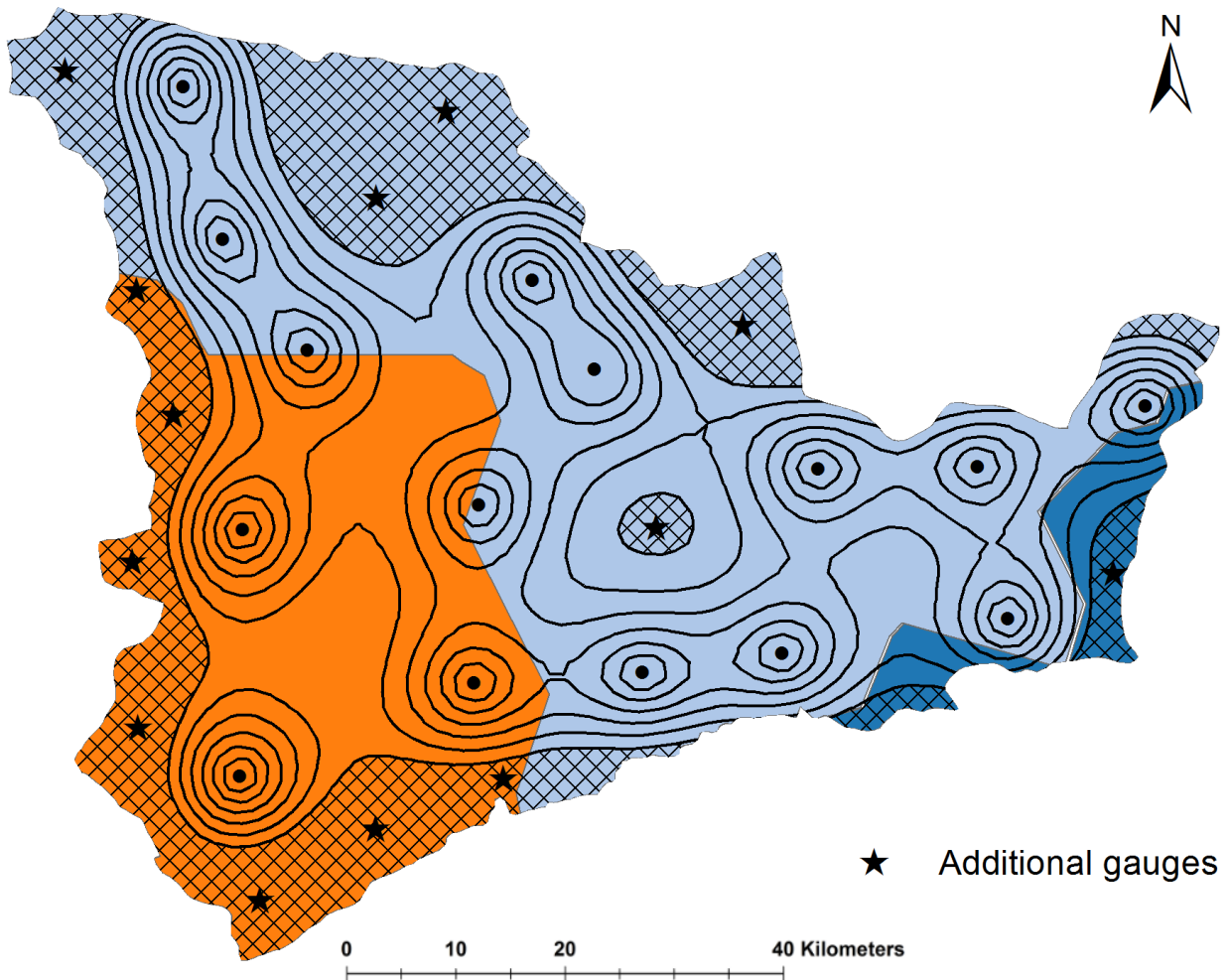


Figure 5-6: Contour map of kriging variance of estimation error for total rainfall in MRGN with additional rain gauges added to the areas where the standard error is more than the threshold of 10%. Map projection: WGS 84 / UTM zone 35S

To test the theoretical effectiveness of the additional gauges to the MRGN using the percentage of area with acceptable accuracy criterion, the kriging variance error for the augmented network was determined. To determine the kriging variance error for the augmented network, the data from 15 gauges (Table 5-1), that was used for estimating the kriging variance error in Figure 5-5,

was again used with the addition of the interpolated values (Table 5-4), at the additional rain gauges (Figure 5-6). This resulted in a new kriging variance error field for the MRGN (Figure 5-7).

Table 5-4: The rainfall amounts at additional rain gauges sites that was determined through kriging of the original MRGN data between 2014-12-10 and 2015-01-11.

Additional Site	16	17	18	19	20	21	22	23	24	25	26	27	28
Rainfall (mm)	137.67	91.36	75.50	122.75	82.77	85.99	128.17	137.34	107.33	112.60	125.39	109.45	114.16

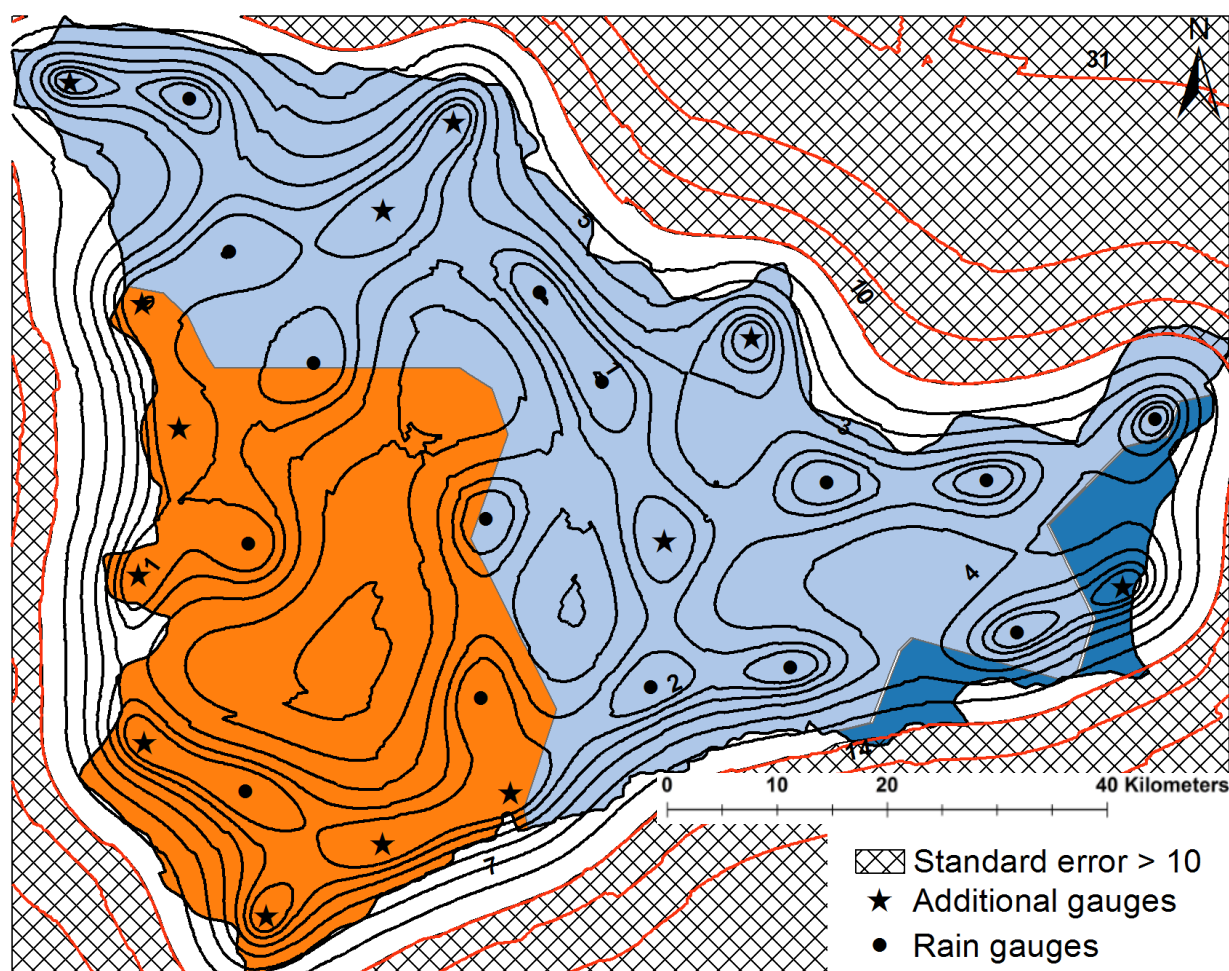


Figure 5-7: Contour map of kriging variance of estimation error for the augmented network, showing the original gauges of the MRGN as well as additional gauges. Map projection: WGS 84 / UTM zone 35S

As shown in Figure 5-7, the percentage of the augmented network with acceptable accuracy greatly improved with the addition of more rain gauges to certain areas of the original network of gauges. The standard error of kriging variance is now less than 10% for almost the entire catchment in which the MRGN is located.

CHAPTER 6 CONCLUSIONS

The purpose of this chapter is to summarize the main findings of the study and relate them to the study's aims and objectives. The main idea was to study the temporal and spatial scale of rainfall and why it is important to be able to quantify these variations.

The way we measure rainfall has greatly changed, and this has had a significant influence on the measurement methods of rainfall. New measuring instruments such as radar and satellite have greatly improved our ability to measure rainfall on a higher resolution in both the temporal and spatial scale, but these sensors are still prone to errors and biases in their measurements. Therefore, with rainfall measurement technology constantly changing, it is important to understand and quantify these errors so that we can determine the continuity of historical measurements.

Rain gauges can give us the longest rainfall record of any device. They are also considered to be the most accurate rainfall measuring instrument and is commonly used as the ground truth to remotely sensed weather monitoring instruments such as radar and satellite.

6.1 The ability of syphon tipping bucket rain gauge to characterise rainfall

Thus, the first objective was to investigate the ability of syphon tipping bucket rain gauge to characterise rainfall. The tipping bucket rain gauge is generally considered to make the most accurate estimates of rainfall. The advantages that tipping bucket rain gauges have over other rainfall measuring instruments such as radar, disdrometer and weather satellite, is the fact that it is much cheaper and more reliable than any of these instruments. The problem with the tipping bucket rain gauge is however, that it is prone to make errors in its estimates during events with high rain rates. These errors are usually associated with false tips being recorded as a result of high rain rates causing the buckets to bounce due to the momentum of water flowing into them, thus recording a tip when no water even accumulated in the other measuring bucket of the rain gauge.

To overcome this problem, the TB3 tipping bucket rain gauge used in this study is equipped with a syphon which regulates the flow of water into the buckets, thus eliminating the danger of high rain rates causing false tips. As most of the measurement errors of a tipping bucket rain gauge is a direct result of high rain rates, this feature of the gauges in the MRGN reduces the percentage of errors by a significant amount. Deriving rain rates from the syphon gauge does however have its own unique challenges. The start and end of rainfall event is buffered due to the 0.4 mm of water firstly accumulating in the syphon before being released onto the tipping buckets. Then as the syphon dumps all the water simultaneously onto the buckets, a double tip is recorded which

is in fact true rainfall data, however the inter-tip time is not realistic. Therefore, in this study a new algorithm had to be developed, which can indicate the start and end times of an event, as well as eliminate the double tip problem.

Other errors that were not associated with high rain rates such as, partially blocked gauges and outside interference were also identified in the data of the MRGN, using automated procedures to look for questionable inter-tip rain rates. The term questionable is used due to the fact that it can never be certain if it was in fact an error that is identified or if it was just a natural occurrence.

The automated quality control checks used in this study can be applied to any operational rain gauge network. They are convenient and reliable and if a network is equipped with modems for communication, these checks can help identify errors in real-time which can then immediately be investigated and fixed without losing long periods of data such as the case in this study

Once the ability of syphon tipping bucket rain gauge to characterise rainfall was investigated and the errors that occurred was eliminated from the data using the various quality control measures described in this study, the spatial variability of rainfall in the catchment could be determined.

6.2 The spatial variability of rainfall in the MRGN

Thus, the second objective of this study was to determine if the existing rain gauges in the MRGN is dense enough to quantify the spatial variability of rainfall. In Figure 4-7, we can see the difference that temporal scale has on the spatial variability. For longer accumulation periods such as the daily data, it can be seen that the rainfall totals are more uniform with less variation in correlation between rain gauges. At the shorter temporal scale of 12 hours there is more variation in rainfall correlations between rain gauges. Therefore, it is important that rain gauge networks that are designed for a specific purpose is carefully evaluated in order to determine what spatial and temporal resolution of data is needed and what is the network's ability to capture the spatial variability of rainfall. If the purpose of a network is to provide information on long-term climate, a less dense network will be sufficient as the spatial variability of rainfall is less over longer periods, as shown in Figure 4-7. However, if a network is designed for calibration of other weather sensors such as radar and satellites, high resolution spatial and temporal data will be needed, thus more rain gauges will have to be installed in the existing network.

6.3 Optimisation of the distribution of gauges in the MRGN

Therefore, the third objective of this study was to find the optimal number and spatial distribution of rain gauges in the MRGN to effectively capture the spatial variability of rainfall. Thus, it was determined that 13 additional rain gauges had to be added to the existing MRGN. This number of additional gauges was calculated using a geostatistical approach where the current network of

rain gauges was evaluated based on the percentage of area within the network that has acceptable estimation accuracy. Through ordinary kriging and the variance of estimation error associated with this interpolation technique, un-gauged sites were identified for placement of new gauges if the estimation accuracy at that particular site is within the acceptable tolerance of variance of estimation error.

Additional gauges to the MRGN was distributed through a trial and error procedure that was dependant on the standard error of estimation in the kriging interpolation method applied to rainfall data of the MRGN. This method is simple and robust and can be applied in the operational environment of even a national rain gauge network.

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APPENDIX A: GENERAL INFORMATION OF RAIN GAUGE SITES

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











Site 6 at Farm - Rooibeers (27.10115, -26.05958)



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



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

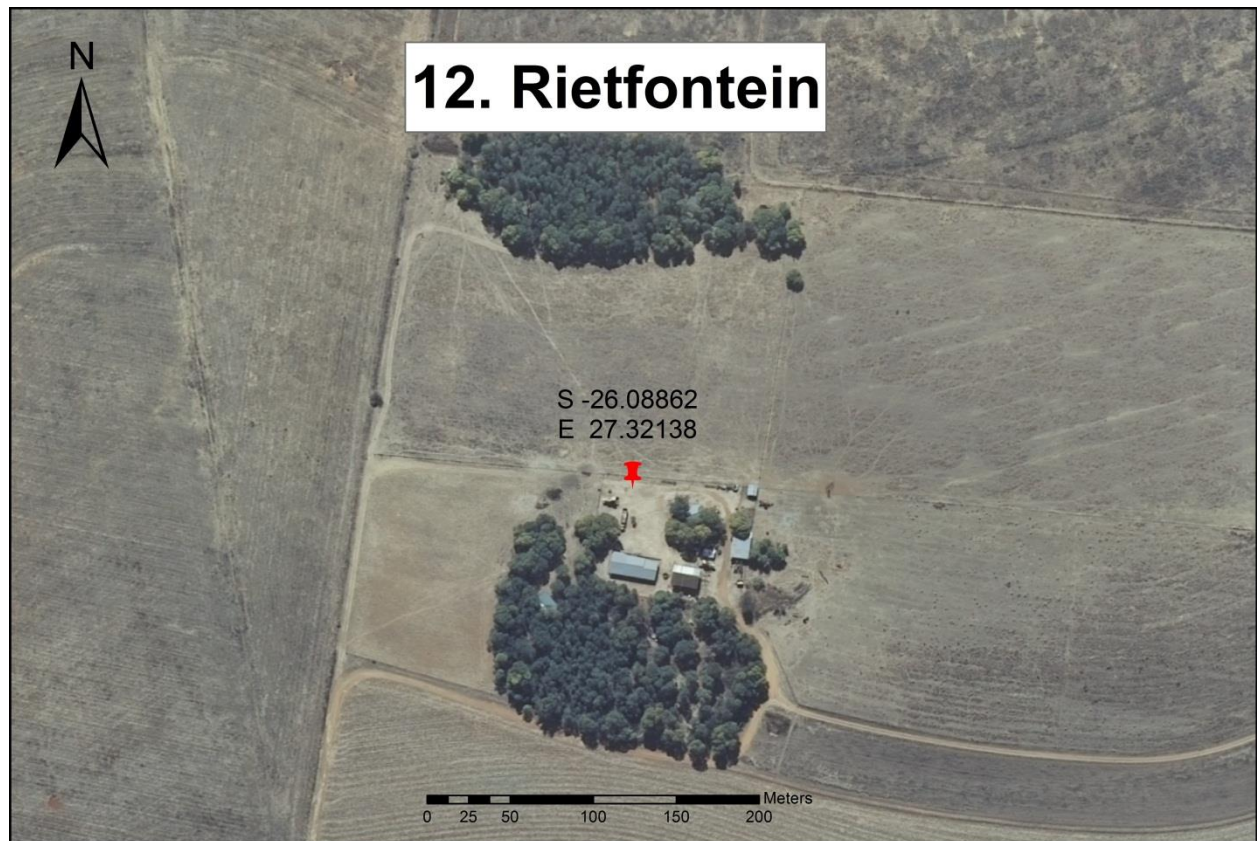


Site 9 at Farm - Leeuwpan (27.28291, -26.2486)









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





