TOWARDS AN IMPROVED UNDERSTANDING OF THE INFLUENCE OF RAINGAUGE DESIGN, SLOPE AND ASPECT ON RAINFALL MEASUREMENTS: A CROSS-CALIBRATION STUDY

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Hydrology, Centre of Water Resources Research, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the Water Research Commission (WRC) of South Africa.

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.

Signed:…………………………..
Byron Gray

Signed:…………………………..
Dr Michele L. Toucher

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I, *Byron Gray*, declare that

- (i) the research reported in this dissertation, except where otherwise indicated, is my original work;
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- (iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons; and
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DECLARATION 2 – PUBLICATIONS

DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part of/or include research presented in this dissertation (including publications submitted and published, giving details of the contributions of each author to the research and writing each publication):

Publication 1 – Chapter 2 of this dissertation

Gray, B and Toucher, M.L. 2017. Towards an improved understanding of the influence of raingauge design, slope and aspect on rainfall measurements: A cross-calibration study. *Submitted to Water SA*

The analysis for this publication was conducted by B. Gray. The publication was written in its entirety by B. Gray and all figures, tables and graphs were produced by the same unless otherwise referenced in the text of the paper. Data collection was conducted by B. Gray and assistance was provided by the South African Environmental Observation Network (SAEON) Grasslands-Forests-Wetlands Node in Cathedral Peak and conducted by SAEON Fynbos Node in Jonkershoek. Editing and advice regarding interpretation was provided by M.L. Toucher.

Publication 2 – Chapter 3 of this dissertation

Gray, B., Toucher, M.L., and Morris. C. 2017. Investigation into the accuracy of current Texas high intensity raingauges and the influence of Nipher shields at a high altitude meteorological station in Cathedral Peak. *Submitted to Weather*

The analysis for this publication was conducted by B. Gray. The publication was written in its entirety by B. Gray and all figures, tables and graphs were produced by the same unless otherwise referenced in the text of the paper. Data collection was conducted by B. Gray and assistance was provided by the SAEON Grasslands-Forests-Wetlands Node. Statistical analysis advice was provided by C. Morris. Editing and advice regarding interpretation was provided by M.L Toucher.

ABSTRACT

There is a lack of research and data around rainfall processes and measurements in mountainous areas due the difficult accessibility and remote nature of these areas, as well as the lack of high altitude raingauges and monitoring networks. The number of recording raingauges have decreased over the past two decades in South Africa. High altitude raingauges, such as those situated in Cathedral Peak and Jonkershoek, are part of a vital high altitude gauging network. The tipping-bucket raingauge, has generally replaced the historical manual raingauges, in rainfall monitoring networks worldwide. With the re-establishment of the Cathedral Peak research catchments and the upgrade of the Jonkershoek research catchments, Texas high-intensity and Davis tipping-bucket raingauges replaced the historical Snowdon raingauges. The accuracy of rainfall volumes captured by currently avaliable tipping-bucket raingauges is a popular debate in hydrology and meteorology. There are several differences between the raingauges, such as measuring mechanism, shielding and angle of inclination. The common consensus is that tipping-bucket raingauges underestimate the actual rainfall occurring. With the change in equipment, there is a need to conduct a cross-calibration between the historical Snowdon raingauge and the current Texas and Davis tipping-bucket raingauges, to ensure the compatibility of current and historical rainfall records. As the Snowdon raingauges were historically used with Nipher shields in the Cathedral Peak research catchments, the long term meteorological station provided the perfect site to conduct a comparison between the Snowdon and Texas tipping-bucket raingauges, as well as to test the influence of shielding the current Texas raingauges at the site. The overall aim of this research, was to improve the understanding of the influences on rainfall measurements in mountainous areas. This research is split into two sections. The aim of the first section of the research was to ensure the compatibility of the historical and current rainfall records of the Cathedral Peak and Jonkershoek research catchments through a cross-calibration study. Beyond this, the influence of altitude, aspect and slope on rainfall measurements was considered. The aim of the second part of the research was to improve the understanding of the influence of a shield and gauge design on rainfall measurement accuracy. Beyond this, the influence of rainfall event characteristics was considered. Eleven raingauge sites at Cathedral Peak and eight sites at Jonkershoek were included in the first section of the study. Concurrent monitoring of the historical and tipping bucket gauges was undertaken for 27 months in Cathedral Peak and 10 months in Jonkershoek. Over this period, a general trend emerged across both catchments. The historical and current raingauges recorded similar rainfall volumes, but with the historical raingauge generally recording more, with the recorded difference never exceeding 12.1% in Jonkershoek and 13.5% in Cathedral Peak. Statistically the differences between the current raingauge and the historical raingauge were not significant, and no confident trend was identified for slope and aspect. From this study, it can be concluded that the difference between the current and historical raingauges is not significant enough to warrant the use of correction factors. The upgrade of equipment to more current, better resolution equipment, should pose no significant problem to change detection and the homogeneity of the rainfall record at two important high altitude monitoring sites. For the second section of the study, a ground level raingauge was used as a reference raingauge to compare measurements to the above ground raingauges. After 20 months of observation, the comparison between the Snowdon raingauge and the Texas raingauge showed that at a monthly time step there was little difference between the gauges, , with the Snowdon raingauge recording 0.7 % more rainfall than the unshielded Texas raingauge. Both the Snowdon and unshielded Texas recorded 7.2 % and 7.9 % less than the ground level raingauge. The shielded Texas raingauge recorded the lowest rainfall, measuring 12 % less than recorded by the ground level. When considering event based rainfall, the unshielded Texas raingauge recorded more rainfall than the shielded Texas raingauge for 52.27 % of the events, with 33.52 % of the events showing no difference between the rainfall measured by the two raingauges. The difference between the shielded and unshielded raingauges is greatest for high intensity, low wind speed events. It can be concluded from this study that there is no requirement for shielding of the current raingauges used in the Cathedral Peak research catchments.

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CHAPTER 1: INTRODUCTION

Rainfall records are crucial in hydrological modelling, decision-making and monitoring for global change. The lack of rainfall records, as well as short or poor records, compromises the quality of hydrological modelling and decision-making (Habib *et al.*, 2004; Lanza and Vuerich, 2012; Pegram *et al.*, 2016).

1.1 Rainfall Measurement in South Africa

The number of active raingauges in South Africa has decreased over the past two decades (Pegram *et al.*, 2016). Based on the Climate Systems Analysis Group (CSAG) data base, recording raingauge numbers peaked in the 1970s with 3261 raingauges, and have since rapidly decreased to approximately 1000 in 2009 (Figure 1.1; Pegram *et al.*, 2016). This declining network is of concern, as the measurement of rainfall needs a denser network than any other meteorological entity because precipitation is highly variable both, spatially and temporally (Steiner *et al.*, 1999; Davie, 2003; Karimi-Hosseini *et al.*, 2011). Having an understanding of the rainfall in such a variable area, and being able to record and produce a good representation of it, is important for understanding the hydrological response of the area (Buytaert *et al.*, 2006). With storm events, which can be common in mountainous areas, rainfall amounts and intensity can vary significantly over distances as small as 1 km (Singh, 1997; Steiner *et al.*, 1999). Therefore, measuring the rainfall using only one gauge provides a poor representation of the catchment’s rainfall (Singh, 1997). The effects of mountainous topography on precipitation, has not been well researched, as accessibility to such areas to conduct research is not easy (Prudhomme, 1998).

Further to this declining network in South Africa, is the lack of high altitude raingauges, with the majority of raingauges located between altitudes of 1000 m and 1700 m, or close to sea level (Figure 1.1; Pegram *et al.*, 2016). As a significant proportion of the country’s water resources are generated at high altitudes (Toucher *et al.*, 2016), water resources decision-making and planning is compromised due to a lack of high altitude rainfall data. Thus, high altitude raingauges, such as those situated in the Cathedral Peak and Jonkershoek long term Research Catchments, are part of a vital high altitude gauging network in important streamflow generating areas of South Africa(Toucher *et al.*, 2016). Measuring rainfall in high altitude, mountainous areas, such as Cathedral Peak and Jonkershoek also provides insight into the rainfall characteristics in areas where gauging networks are rare (Toucher *et al.*, 2016), as well as monitoring for global change.

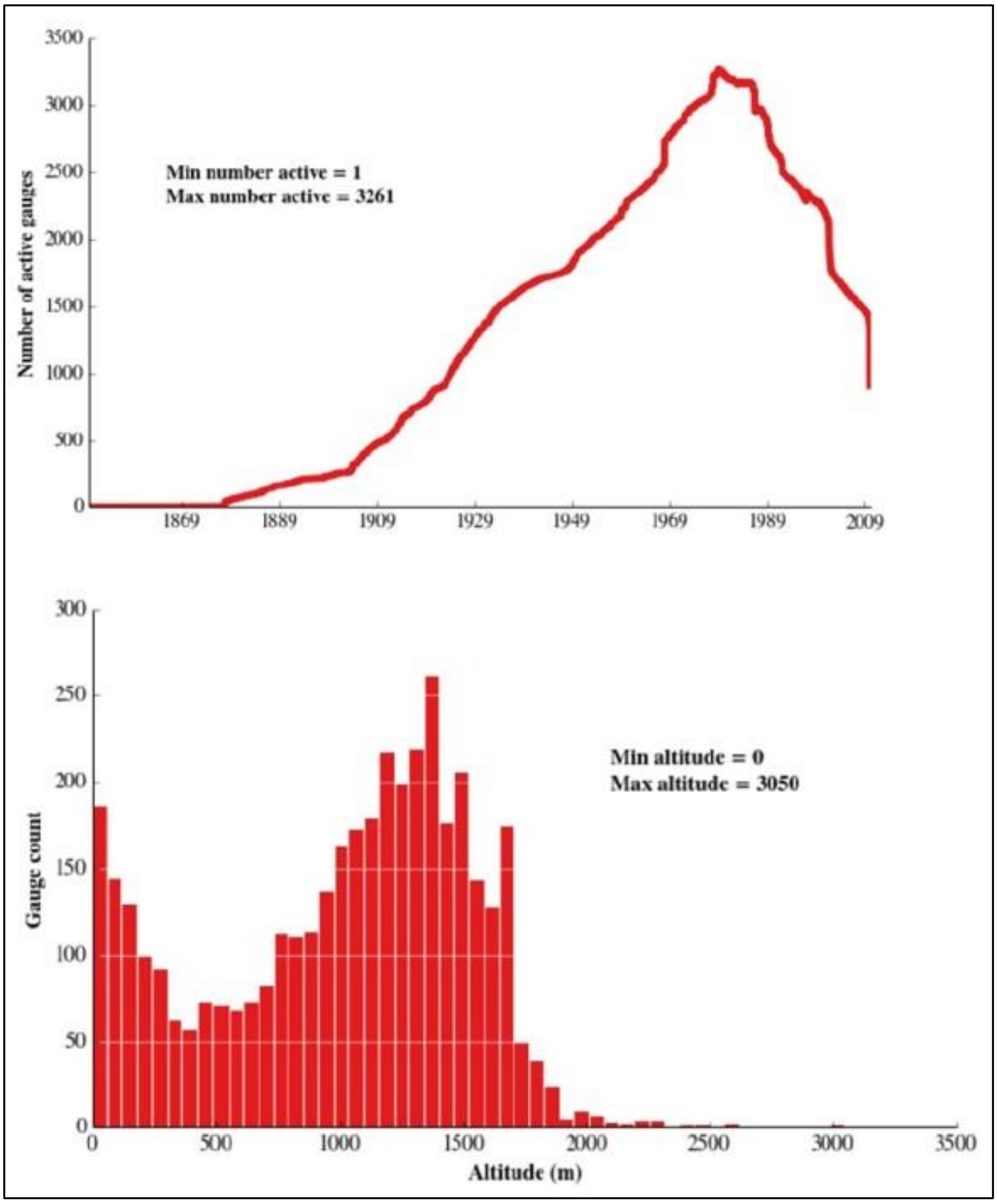

Figure 1.1 Raingauge network trends (top) and distribution of raingauges with altitude (bottom) across South Africa according to the CSAG data base (Pegram *et al.*, 2016)

In order to determine changes in the climate and subsequent impacts, long-term, homogenous series of data are needed (Bartokova *et al.*, 2014), as it is important that any changes identified in the data are the result of the change in climate and not artificial changes (Bartokova *et al.*, 2014). It is, however, hard to prevent these artificial changes such as changes in the vegetation or equipment. Furthermore, it is often necessary to upgrade equipment in order to get better measurements or a better resolution measurements that becomes possible with advances in measurement techniques and dataloggers (Bartokova *et al.*, 2014). If these changes are properly managed, their impacts on the homogeneity of the data is reduced (Bartokova *et al.*, 2014). When changing equipment, there should be a period where the new equipment measures alongside the equipment being replaced. This should be over a period sufficient for the variability of the climate component being measured, to allow for a cross-calibration between the new and the old equipment (Bartokova *et al.*, 2014). This period is much greater for a highly temporally variable component such as precipitation (Bartokova *et al.*, 2014).

As mentioned previously, there are few high altitude raingauge stations in South Africa. Thus, the raingauges in the Cathedral Peak and Jonkershoek high altitude catchments are of key importance. These long-term research sites were established in the 1930's to investigate the effects of commercial forestry and other land use practices on streamflow (Toucher *et al.*, 2016), with continuous monitoring at the Jonkershoek site from 1935 (Van Wyk, 1987) and at the Cathedral Peak site from 1949 to 1994 (Everson *et al.*, 1998). In 1995, funding ceased for the Cathedral Peak site, thus monitoring stopped (Toucher *et al.*, 2016). In 2012, monitoring was re-established in the Cathedral Peak catchments and an upgrade of the Jonkershoek research catchments was undertaken by the South African Environmental Observation Network (SAEON). Texas high-intensity and Davis tipping-bucket raingauges were installed to replace the historical Snowdon raingauges. With the change in equipment, differences in the measurement of rainfall are expected, affecting the homogeneity of the rainfall records for the Cathedral Peak and Jonkershoek research catchments. These two sites have substantial rainfall records, and therefore are vital for the long-term monitoring of global change in South Africa.

1.2 Types of Raingauges

With the change from the historical Snowdon raingauges to the current tipping-bucket raingauges, there is concern regarding the homogeneity of the rainfall records, as there are several differences between these raingauges and their measurement of rainfall. Tipping-bucket raingauges are the most common form of raingauge currently in use (Molini *et al.*, 2001; Strangeways, 2010; Tapiador *et al.*, 2012). Generally, the most commonly used tipping-bucket raingauge has the ability to measure rainfall with an accuracy of "0.2 mm" (World Meteorological Organisation, 2008). Tipping-bucket raingauges record the rainfall as it occurs, thus are event based and provide information regarding rainfall intensities (Habib *et al.,* 2001; Chang, 2006). Tipping-bucket raingauges typically do not have shields placed around them (Devine and Mekis, 2008). The common consensus is that this type of gauge underestimates the actual rainfall occurring (Molini *et al.*, 2005; Colli *et al.,* 2014) due to the manner in which the tipping-bucket mechanism works. A tipping-bucket raingauge mechanism (Figure 1.2) works by collecting rainfall in the funnel which then fills the top bucket, causing the bucket to tip and force the magnet to pass the switch indicating a tip has occurred. By calibration in the laboratory, the amount of water that produces a tip, can be determined and is entered into the datalogger program (WMO, 2008). Tipping-bucket raingauge mechanisms are also sensitive to small disturbances (Scuito *et al.*, 2009). Molini *et al.* (2005) states that the errors created by the mechanical nature of the tipping-bucket raingauge, are often ignored when the rainfall data is considered. These errors are seen to have little, to no effect on the total rainfall recorded by the raingauge over a period of sufficient time, but only on the rainfall intensity and rate measurement (Molini *et al.*, 2005; Shelton, 2009; Colli *et al.*, 2014).

Snowdon raingauges are considered to provide a good representation of the actual rainfall due to their large funnel and accurately constructed rim (Burt, 2013). A non-recording raingauge such as the Snowdon raingauge, is commonly used in mountainous areas, as they have large storage containers for monthly measurement (Shaw, 1994; Chang, 2006). The Snowdon raingauge storage container is designed to reduce the exposure to solar radiation, in order to prevent evaporation (WMO, 2008), however it may overflow with large events causing an underestimation of the rainfall measurement (Ward and Robinson, 2000). To prevent the evaporation of the collected rainfall, the WMO (2008) suggests the use of an "oil film" to create a layer on the surface of the collected rainfall, acting as a buffer between it and the atmosphere. Snowdon raingauges were commonly used with wind shields such as the popular Nipher shield (Figure 1.2). The Nipher shield is similar in shape to an “inverted cone” and is used to bend the wind around the raingauge in such a way that the air directly above the orifice is undisturbed (De Villiers, 1990; Duchon and Essenberg, 2001). The Nipher shield’s inverted cone shape is designed to force the wind downward away from the orifice (De Villiers, 1990; Devine and Mekis, 2008). The shield creates a smooth air flow over the orifice of the raingauge, with similar speed and characteristics to those of wind in an open field (Devine and Mekis, 2008).

A raingauge that is the least affected by wind is that of the ground level raingauge (Figure 1.2). This type of raingauge, as the name suggests, is placed with its orifice at ground level, either using a manual or an automatic raingauge, but are not commonly found in raingauge networks. The raingauge is commonly placed in a pit in the ground which is surrounded by a grid (WMO, 2008). The grid is used to prevent in-splash into the orifice, as well as to decrease the effects of the wind around the orifice (WMO, 2008; Mekonnen *et al.*, 2014). Ground level raingauges are considered to provide the most accurate measurement of rainfall (Dreaver and Hutchinson, 1974; Chang, 2006; Rodda and Dixon, 2012; Mekonnen *et al.*, 2014) due to the reduced wind effects on the ground level gauge. The WMO considers them as reference gauges, against which other precipitation gauges should be compared (Mekonnen *et al.*, 2014). A possible reason for their low adoption, is that they require a pit to be dug and drainage of that pit needs to be considered (Dreaver and Hutchinson, 1974; Chang, 2006). This is a disadvantage when the site is remote and regular visits are not possible (Dreaver and Hutchinson, 1974). Ground level raingauges are also susceptible to blockages from biological detritus as well as damage from animals, being at ground level (Chang, 2006).

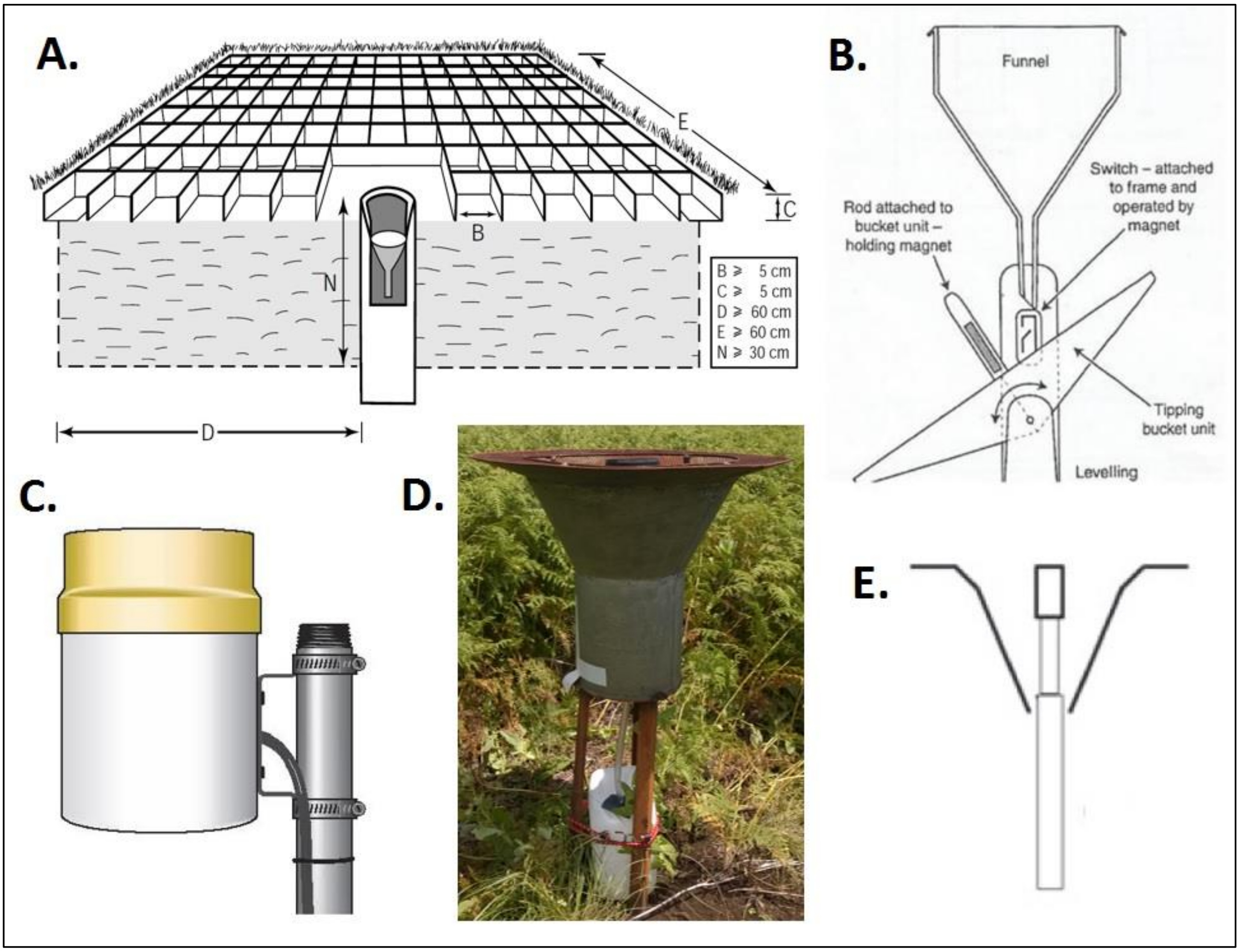

Figure 1.2 An illustration of the different types of raingauges used, (A) the recommended design of a ground level raingauge with grid (WMO, 2008), (B) the tipping-bucket mechanism, (C) the Texas tipping-bucket raingauge exterior which hosts the mechanism (Toucher *et al*., 2016), (D) a Nipher shield with Snowdon replica raingauge used in Cathedral Peak and (E) the layout of a Nipher shield (Strangeways, 2010).

1.3 Errors in Rainfall Measurement

Rainfall can be considered as the simplest hydrological component to measure, however, it is difficult to measure accurately (Davie, 2003). “Theoretically, the true values of hydrological elements cannot be determined by measurements because errors of measurement cannot be eliminated completely” (WMO, 2008). Therefore, what is measured in the field is not an exact indication of what occurred. However, by reducing the errors, a closer representation of the natural system can be achieved. The errors in rainfall measurement are the result of natural factors, such as wind, evaporation and temperature (Michelson, 2004; Colli *et al.*, 2014). In rainfall measurement, both systematic and random errors occur (Tokay *et al.*, 2003; Mekonnen *et al.*, 2014). Wind effects, raingauge design differences, evaporation losses and rain splash are examples of systematic errors (Tokay *et al*., 2003; WMO 2008). Blockages of the raingauges, mechanism disturbances, datalogger errors and human error are examples of random error (Sevruk, 1996). The impact of random error is greatest for tipping-bucket raingauges (Sevruk, 1996). Systematic errors can be determined and corrected for, while random errors cannot (WMO, 2008). To prevent these errors, the selection of the site for the raingauge is important, as well as the type of raingauge, the methods to prevent evaporation, wind effects and out-splash (WMO, 2008).

Systematic errors which occur during the recording of rainfall are mainly the result of wind and its influence over the orifice of the raingauge (Michelson, 2004; Sugiura *et al.*, 2006; Mekonnen *et al.*, 2014). According to the WMO (2008), wind has the greatest influence on the rainfall catch of a raingauge (Michelson, 2004; Devine and Mekis, 2008). There are two effects of wind to focus on. The effect of the raingauge as an obstruction to the flow of wind, and the effect of the landscape and site on wind flow (Green, 1970; Dreaver and Hutchinson, 1974; De Villiers, 1990; WMO, 2008). In the natural environment, wind is turbulent and non-uniform over the earth's surface (Strangeways, 2004). When the wind approaches the raingauge, it may alter its path and take several paths around the raingauge, thus causing a disturbed airflow over the orifice (Strangeways, 2004). This can result in a 35% increase in the speed of the wind over the orifice of the raingauge (Devine and Mekis, 2008). As a result light raindrops can be carried away, causing an under-estimation of rainfall (Strangeways, 2004).

The underestimation of rainfall due to wind is determined by two factors, the wind speed and the raindrop diameter (Davie, 2003). Chvíla *et al.* (2005) found that there is a difference between under-catch, due to wind during convective precipitation, and non-convective precipitation, with the non-convective precipitation creating the greater error. With a smaller rain drop diameter, the effects of wind on rainfall readings increase (Chvíla *et al.*, 2005). Convective rainfall events tend to have a larger rain drop diameter than non-convective rainfall events, with the same intensity (Chvíla *et al.*, 2005). Chvíla *et al.* (2005) also found that the error created by wind, increased with an increasing wind speed and decreasing rainfall intensity. This is again as a result of rain drop diameter which decreases with a decreasing intensity. The effect wind has is greater for solid forms of precipitation, than liquid forms (Chang, 2006).

A further natural cause of a systematic error in rainfall measurement is that of evaporation. There are several ways that water can evaporate from the raingauge and cause inaccurate readings. This first occurs when water from a rainfall event remains in the funnel or along the sides of the raingauge, and is then evaporated (Devine and Mekis, 2008; Mekis and Hogg, 2010). Evaporation also occurs when the water is left in the funnel or remains stuck to the raingauge walls by cohesion after emptying (Davie, 2003; Mekonnen *et al.*, 2014). This water evaporates and is not recorded by the raingauge (Mekis and Hogg, 2010). These are also known as wetting losses (Yang *et al.*, 1999; Davie, 2003). With the tipping-bucket raingauge, water may remain in the bucket during light rainfalls, exposing it to evaporation before it can be recorded as a tip (Wang *et al.*, 2006). As a result, evaporation losses will be dependent on, and vary with, rainfall events and intensities (Seibert and Morén, 1999; Yang *et al.*, 1999), as well as with the time of year, having a greater influence during the wet season (Yang *et al.*, 1999). The loss as a result of evaporation can also vary with raingauge design and age of the raingauge (Seibert and Morén, 1999; Yang *et al.*, 1999). With the application of a small volume of oil to the raingauge to prevent evaporation, Devine and Mekis (2008) found a reduction of 0.5 $mm.h^{-1}$ in the evaporation rate from a Snowdon raingauge during the day. The placement of oil into the raingauge can provide a more accurate rainfall measurement, especially for monthly raingauges.

Method of measurement can also have an influence on the difference in rainfall recorded between two raingauges used for different purposes. Hydrologists are interested in the amount, timing and location of rainfall which reaches the ground as well as the rainfall intensity (Essery and Wilcock, 1991). Meteorologists are interested in how much rainfall fell, and what was responsible for its occurrence, they are not interested in it once it has reached the ground (Ward and Robinson, 2000). For measurements of rainfall for hydrological purposes, the raingauge should therefore be sited at the same angle as the slope with the orifice parallel to the ground (Beullens *et al.*, 2014) as illustrated in Figure 1.2. Rainfall measured for meteorological purposes is recorded by a raingauge with the orifice parallel to the horizon (Beullens *et al.*, 2014). This results in a different rainfall measurement for meteorological and hydrological raingauges. This difference will be greatest on steep slopes (Ward and Robinson, 2000). When the rainfall is falling at an angle across a catchment, either due to wind or topography, there is an expected difference between the hydrological and the meteorological raingauges. Meteorological raingauges placed on a steep slope will have higher rainfall readings than hydrological raingauges when the wind is blowing down the slope (Hamilton, 1954; Ward and Robinson, 2000). When the wind is blowing up the slope, the meteorological raingauges will measure less rainfall than the hydrological raingauges (Hamilton, 1954; Ward and Robinson, 2000). Hamilton (1954) conducted an extensive study and found through comparisons between vertical and tilted gauges with a “control catchment surface”, that in mountainous catchments the greatest error in rainfall catch resulted from placing the raingauges vertically. They also tested shielding and found that the raingauge shield had little effect and was no replacement for placing the raingauge at the same angle as the slope. Hamilton (1954) also noticed that the tilted raingauges were only more accurate on the slopes where the tilted gauges faced the prevailing weather.

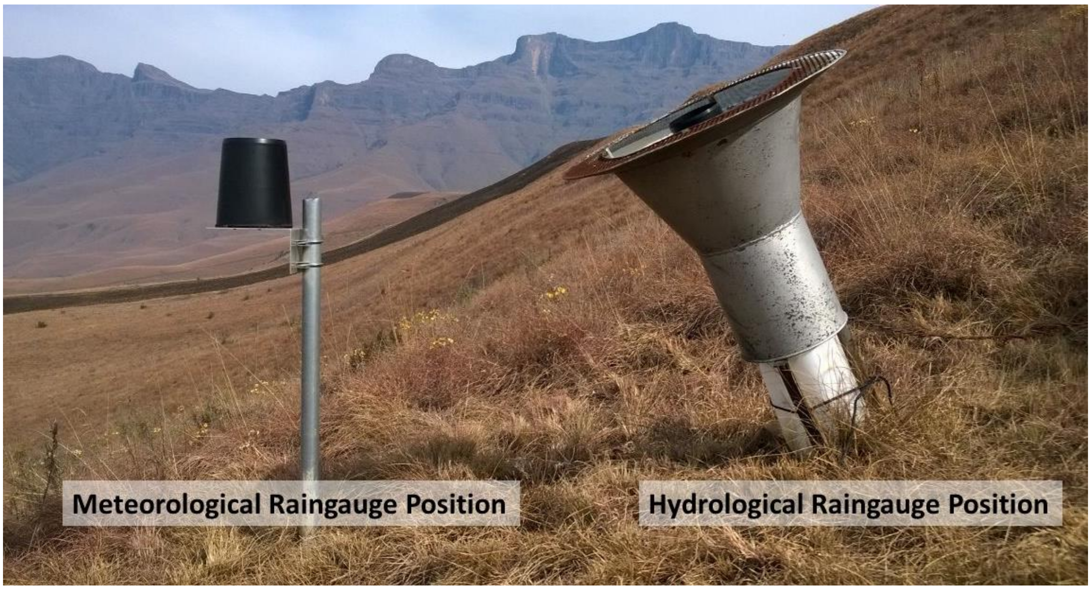

Figure 1.3 A representation of the difference between hydrological and meteorological raingauge positions.

It is suggested that for long term monitoring, a hydrological raingauge will provide a more accurate representation of the rainfall falling on the slope, than a meteorological raingauge (Barry, 2008). In literature, it is highly advised to place raingauges at the same angle as the slope in mountainous areas (Hamilton, 1954; De Villiers, 1990; Davie, 2003; Chang, 2006).

Meteorological raingauges are the most commonly used. As hydrological models are calibrated using data collected by meteorological raingauges, there needs to be a better understanding of the relationship between the more accurate hydrological raingauges and the meteorological raingauges, to improve the calibration of the models. Cathedral Peak and Jonkershoek provide the ideal opportunity to investigate this relationship.

1.4 The Long-Term Research Sites used in this study

The Cathedral Peak and Jonkershoek catchments are both long-term research sites with substantial climatic and hydrological records. These two sites were established to investigate the impacts of land use and land management treatments on water resources in the winter (Jonkershoek) and summer (Cathedral Peak) rainfall regions of South Africa (Nanni 1953).

1.4.1 History of Cathedral Peak and Jonkershoek

Jonkershoek, established in 1935 (Wicht, 1940), played an important role in initiating catchment research programs in South Africa (Kruger and Bennett, 2013). This lead to eight other research programs which included “49 gauged catchments” spread across South Africa (Kruger and Bennett, 2013). One of the catchments to follow Jonkershoek was the Cathedral Peak research catchments in 1938 (Kruger and Bennett, 2013). Jonkershoek was established to investigate methods to improve water supplies as well as to investigate the effects of commercial forestry on streamflow (Van Wyk, 1987). Jonkershoek consisted of eight research catchments (Smith and Scott, 1992) with 15 permanent raingauges installed in 1935 (Wicht, 1940). The time step at which these were read depended on their accessibility. Five of the gauges that were easily accessible were measured daily and were “standard five-inch” gauges (Wicht, 1940). A further five eight-inch “Casella Siphon Rainfall Recorders” that were less accessible were measured weekly (Wicht, 1940). Five “standard five-inch” gauges that were installed at inaccessible sites were measured monthly (Wicht, 1940). Other gauges were added to the catchments temporarily depending on the need for selected research (Wicht, 1940). Wicht (1940) conducted an analysis of precipitation at Jonkershoek and found that more rainfall occurred towards the head of the valley, with July being the wettest month. The rainfall in Jonkershoek occurs as “long duration, low intensity, frontal events” during the winter months, with the majority of the rainfall occurring between April and October (Armstrong *et al*., 1996).

As mentioned, Cathedral Peak was established following the example at Jonkershoek, to be the summer rainfall region research site to test the effects of land management practices on streamflow through a paired catchment experiment (Kruger and Bennett, 2013; Toucher *et al.*, 2016). The research site was established in 1938 (Toucher *et al.*, 2016) but climatic monitoring only started in 1948 (Nanni, 1956; Schulze, 1974). The Meteorological station consisted of thermometers, recording thermograph and hydrograph, sunshine recorder, evaporation tank and a daily eight-inch recording raingauge and 5-inch manual raingauge with a Nipher shield, which were all measured at 08H00 daily (Nanni, 1956). In 1950, a further 14 raingauges were installed into the catchments (Schulze, 1974). By the end of 1963 there were 23 raingauges installed in the ten research catchments, with an additional three gauges located at the Meteorological station (Schulze, 1974). These raingauges consisted of two different types, the Casella siphon rainfall recorders and standard five inch Snowdon type storage gauges which were fitted with Nipher shields and angled with their orifices at the same angle as the slope (Nanni, 1956; Schulze, 1974). The 11 Casella siphon rainfall recorders would record rainfall at a weekly time step, while the 12-remaining standard Snowdon type storage gauges were measured at a monthly interval (Schulze, 1974). In 1970, four of these monthly raingauges were changed to weekly (Schulze, 1974). These raingauges were labelled according to their location and measurement period. The gauge number described the catchment it was located in, with the following letter indicating whether it was at the top (A), middle (B) or bottom (C) of the catchment. Recording raingauges were labelled with the letter R after their name, to indicate that it was a recording raingauge. Initially, ten catchments were delineated for monitoring and to test various land management treatments, with a further five catchments added in 1972 (Toucher *et al.*, 2016). Monitoring at Cathedral Peak continued until 1995 when funding ceased (Toucher *et al.*, 2016). Over the years, Cathedral Peak has provided the data which has led to important findings by Nanni and others on the water use of commercial forestation. These findings have influenced South African water policy over the years. The data from this site has also been used extensively in model development eg. Schulze and Everson (Toucher *et al.*, 2016).

1.5 Research Aims and Objectives

With the lack of high altitude raingauges in the mountainous areas of South Africa, there is the need to ensure that the current raingauges are providing an accurate measure of rainfall.

This is part of the overall aim of this research, which is to improve the understanding of the influences on rainfall measurements in mountainous areas. With the re-establishment of the Cathedral Peak research catchments in 2012, and the upgrade of the monitoring network at Jonkershoek, the change from the historical Snowdon raingauges, to the more modern Texas high-intensity and Davis tipping-bucket raingauges, has brought about the need for a cross-calibration between the new and the old equipment. Thus, the first objective of this research was to conduct the cross-calibration to determine if there are any differences between the historical and current raingauges (Chapter 2). This will determine if there is an influence resulting from the change in equipment, and whether there is a need for correction factors to allow for the continued long-term monitoring of global change at the respective mountainous catchments. Beyond this, a further objective was to understand the influence of altitude, aspect and slope as well as raingauge design on rainfall measurement. This was investigated along with the cross-calibration, making use of the varying physical characteristics of the raingauge networks at both Cathedral Peak and Jonkershoek research catchments. The third objective was to determine the influence of raingauge shielding and design in mountainous areas and whether rainfall event characteristics have an influence on these two factors (Chapter 3). This was conducted at the Cathedral Peak meteorological station making use of the reference ground level raingauge. From this research, the final objective was to provide information and advice on the best practices in terms of raingauge design and setup for mountainous catchments in South Africa, with a focus on Cathedral Peak and Jonkershoek research catchments (Chapter 4).

Following the approach now accepted by the University of KwaZulu-Natal, this dissertation is structured such that findings of the research are written as a series of two research papers marked for publication in peer reviewed journals. A literature review relevant to the specific step in the methodology being covered is provided in each research paper. As outlined in the University of KwaZulu-Natal's dissertation guidelines the referencing style for each of the research papers adhere to the journal for which the paper is intended.

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Lead into Chapter 2

Chapter 2 focusses on the first objective, namely to conduct the cross-calibration between the current and historical raingauges in Cathedral Peak and Jonkershoek. The physical characteristics of the respective sites, such as altitude, aspect and slope, will also be considered, to determine their influences on rainfall measured between the current and historical raingauges. Raingauge design is also investigated in this chapter as a possible influence.

CHAPTER 2: TOWARDS AN IMPROVED UNDERSTANDING OF THE INFLUENCE OF RAINGAUGE DESIGN, SLOPE AND ASPECT ON RAINFALL MEASUREMENTS: A CROSS-CALIBRATION STUDY

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ABSTRACT

High altitude raingauges, such as those situated in Cathedral Peak and Jonkershoek, are a vital part of the raingauge network in South Africa. With the re-establishment of the Cathedral Peak research catchments and the upgrade of the Jonkershoek research catchments, Texas high-intensity and Davis tipping-bucket raingauges replaced the historical Snowdon raingauges. There are several differences between the raingauges, such as measuring mechanism, shielding and angle of inclination, which could influence the measurement of rainfall. The aim of the study was to ensure the compatibility of the historical and current rainfall records of the Cathedral Peak and Jonkershoek research catchments through a cross-calibration study. Beyond this, the influence of altitude, aspect and slope on rainfall measurements was considered. Eleven raingauge sites at Cathedral Peak and eight sites at Jonkershoek were included in the study. Concurrent monitoring of the historical and tipping bucket gauges was undertaken for 27 months in Cathedral Peak and 10 months in Jonkershoek. Over this period, a general trend emerged across both catchments. The historical and current raingauges recorded similar rainfall volumes, with the historical raingauge generally recording more with the recorded difference never exceeding 12.1 % in Jonkershoek and 13.5 % in Cathedral Peak. Statistically the differences between the current raingauge and the historical raingauge were not significant, and no confident trend was identified for slope and aspect. The study concluded that the difference between the current and historical raingauges at the two specific sites considered is not significant enough to warrant the use of correction factors. The upgrade of equipment should pose no significant problem to change

detection and the homogeneity of the rainfall record at these two important high altitude monitoring sites.

2.1 Introduction

Rainfall records are crucial in hydrological modelling, decision-making and monitoring of global change. Added to this, the measurement of rainfall needs a denser monitoring network than any other meteorological entity, because of the high spatial and temporal variability of precipitation (Steiner *et al.*, 1999; Davie, 2003; Karimi-Hosseini *et al.*, 2011). The lack of rainfall records, as well as short or poor records, compromises water resources management (Habib *et al.*, 2004; Lanza and Vuerich, 2012; Pegram *et al.*, 2016). Despite this, the number of recording raingauges in South Africa have decreased from a peak of 3 261 raingauges in the 1970s to approximately 1 000 in 2009 (Pegram *et al.*, 2016). Further to this, is the lack of raingauges located above 1 700 m.a.s.l (Pegram *et al.*, 2016). Beyond being significant water generating areas (Toucher *et al.*, 2016), high altitude, mountainous areas have been shown to be highly sensitive to climate change (Rangwala and Miller, 2012; Kulkarni *et al.*, 2013). The best possible use needs to be made of raingauge records from high altitude areas and there needs to be confidence in the records.

For the monitoring of global change and water resources planning, high altitude raingauges are crucial. The gauges situated in the high altitude Cathedral Peak and Jonkershoek catchments, are a vital part of the gauging network in South Africa as they are situated in important streamflow generating areas (Toucher *et al.*, 2016). These long-term research sites, established in the 1930's to investigate the effects of commercial forestry and other land use practices on streamflow (Toucher *et al.*, 2016), monitor precipitation and other hydrological variables. Monitoring started in the Jonkershoek catchments from 1935 (Van Wyk, 1987) and continues currently. In the Cathedral Peak catchments monitoring started in 1949 (Everson *et al.*, 1998) and continued until 1995 when funding ceased (Toucher *et al.*, 2016). In 2012, monitoring was re-established in the Cathedral Peak catchments and an upgrade of the equipment in the Jonkershoek research catchments was undertaken. Texas high-intensity and Davis tipping-bucket raingauges were installed to replace the historical Snowdon raingauges at both sites. To determine the influence of this change in equipment on the rainfall records, a cross-calibration between the new and the old raingauges in the respective catchments became necessary.

Long-term, homogenous series of data are needed (Bartokova *et al.*, 2014) for climate change studies to ensure that changes identified are the result of changes in the climate and not artificial changes (Bartokova *et al.*, 2014). Artificial changes are, however, often unavoidable. For example, upgrades to the equipment, such as in Cathedral Peak and Jonkershoek, as there are continual advances in measurement techniques and resolutions(Bartokova *et al.*, 2014). If these changes are managed properly, their impacts on the consistency of the data records can be reduced (Bartokova *et al.*, 2014). When changing equipment, there should be a concurrent period of monitoring to allow for a comparison. The length of this period is dependent on the climate component being measured, (Bartokova *et al.*, 2014) and should be longer for a component, such as precipitation, that is highly temporally variable (Bartokova *et al.*, 2014).

In the past, manual raingauges which were measured at selected time intervals, such as the Snowdon raingauges used in Cathedral Peak and Jonkershoek catchments, were common (Wicht, 1940). Nowadays automated tipping-bucket raingauges such as the Texas high-intensity and Davis tipping-bucket raingauge, are prevalent (Molini *et al.*, 2001; Strangeways, 2010; Tapiador *et al.*, 2012). When comparing rainfall data recorded by two different gauges, there are expected differences, due to factors which affect the gauge's ability to capture the actual rainfall. These factors include wind effects, wetting losses and the variability in rainfall intensity and ambient temperature (De Villiers, 1990; Yang *et al.*, 1998; Ciach, 2003; Davie, 2003; Shelton, 2009; Lanza and Vuerich, 2012; Colli *et al.*, 2014). In addition to these factors, the raingauge design also influences the rainfall catch. Tipping-bucket raingauges measure rainfall with a resolution of around "0.2 mm" (WMO, 2008) and have the ability to record continuously (Habib *et al.*, 2001; Chang, 2006). However, these gauges are considered to underestimate the actual rainfall occurring (Molini *et al.*, 2005; Colli *et al.*, 2014), due to their tipping-bucket mechanism limitations. During high intensity rainfall, the tipping-bucket gauge can only tip, empty and fill, at a certain rate (Molini *et al.*, 2005; Scuito *et al.*, 2009) and the volume of rainfall not being measured increases with increasing rainfall intensity (Molini *et al.*, 2005; Scuito *et al.*, 2009). With light intensity rainfall, the tipping-bucket gauge performs poorly, as the light rainfall takes a long time to cause a tip, and the water in the bucket may be exposed to evaporation (Habib *et al.*, 2001). A further source of error is that a small disturbance of the tipping-bucket gauge can cause a tip when there is no rainfall, as the tipping mechanism is sensitive (Scuito *et al.*, 2009). These gauges are also highly susceptible to blockages from natural sources such as biological detritus (Steiner *et al.*, 1999;

Upton, 2002). Data corruption or malfunctioning of the datalogger is a further potential source of error when using an automated tipping-bucket raingauge (Scuito *et al.*, 2009).

Snowdon raingauges provide a good representation of the actual rainfall, due to their large funnel and accurately constructed rim (Burt, 2013). They are also commonly used with a Nipher shield which creates a smooth flow of air over the orifice of the raingauge, reducing the effects of wind (Devine and Mekis, 2008). The Snowdon raingauges in Cathedral Peak and Jonkershoek catchments were sited at the same angle as the slope with the orifice parallel to the ground (Beullens *et al.*, 2014), thereby providing a good representation of the rainfall reaching the ground (Barry, 2008). With the Snowdon gauges, the measurement of rainfall requires a measuring cylinder or dip stick, and this combined with human error in the measurement process can result in inaccurate readings (Devine and Mekis, 2008). If a large event occurs, the rainfall may overflow the storage container causing an underestimation of the rainfall measurement (Ward and Robinson, 2000). Between measurement periods, the rainfall in the storage container is susceptible to evaporation, however a liquid such as paraffin added to the storage container can reduce this effect (Devine and Mekis, 2008).

Given the errors associated with raingauges and the spatial variability of rainfall, several authors (e.g. Essery and Wilcock, 1991; Mekonnen *et al.*, 2014), conclude that site specific correction factors need to be developed when a change in gauge occurs. Additionally, by understanding the relationship between the current and historical raingauges, as well as the influence of natural factors such as aspect, altitude and slope, the impact on the homogeneity of the data can be reduced (Bartokova *et al.*, 2014).

The aim of this study was to ensure the compatibility of the historical and current rainfall records recorded in the Cathedral Peak and Jonkershoek research catchments, South Africa. To achieve this, a cross-calibration of the current and historical raingauges was conducted at both the Cathedral Peak and Jonkershoek research catchments. Furthermore, the influence of altitude, aspect or slope on differences between the historical and current raingauges was investigated, as well as the influence of gauge design, tilt and shielding.

2.2 Methodology

Two important long-term, high altitude monitoring sites, namely the Cathedral Peak research catchments located in the summer rainfall region in KwaZulu-Natal, and the Jonkershoek research catchments located in the winter rainfall region of the Western Cape (Figure 2.1) were the focus of this study. These catchments and their associated raingauge networks are detailed below.

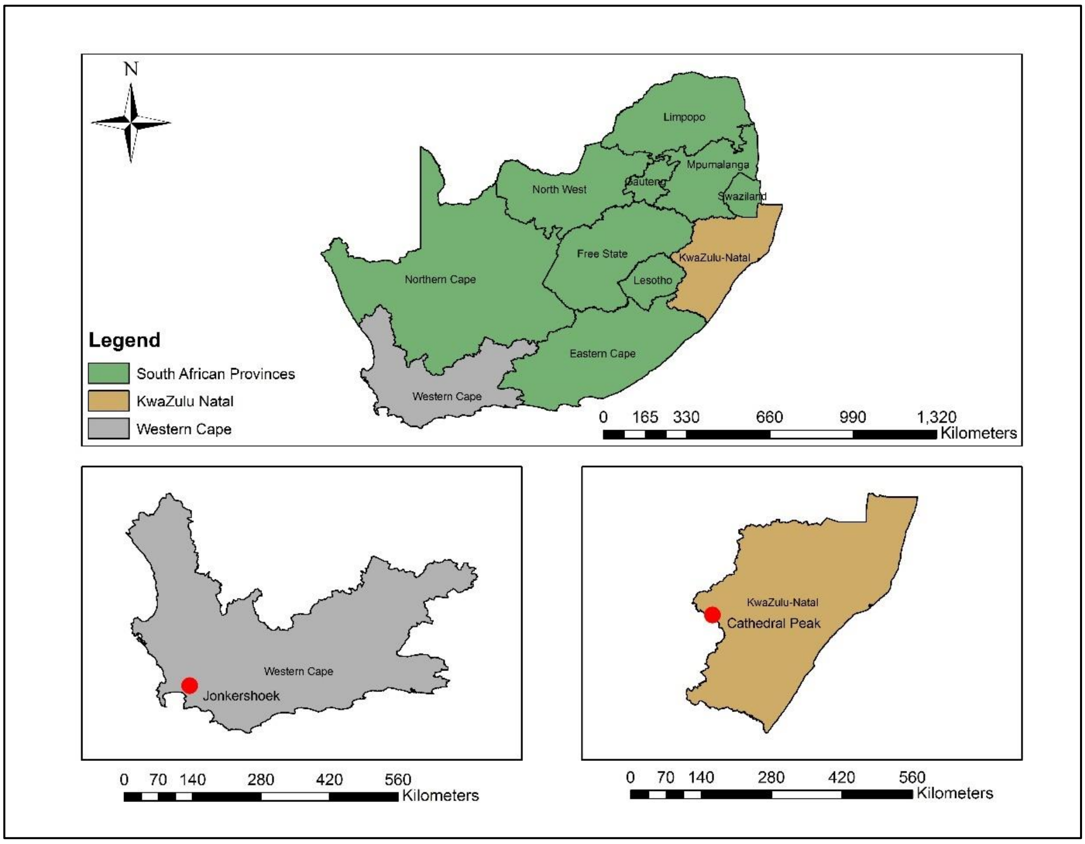

Figure 2.1: Location of the Cathedral Peak research catchments in KwaZulu-Natal and the Jonkershoek research catchments in the Western Cape, South Africa

2.2.1 Cathedral Peak research catchments

The Cathedral Peak research catchments (28°58’32.12”S; 29°14’8.70”E) are situated on the “Little Berg plateau” in the Drakensberg, KwaZulu-Natal, South Africa (Nanni, 1956). The mean annual precipitation (MAP) for the Cathedral Peak research catchments is approximately 1 400 mm per annum (Bosch, 1979). Most of the precipitation occurs during the summer period, as localised thunderstorms, with January experiencing the most rainfall (Nanni, 1956). Ten research catchments were originally delineated in the late 1930s (Figure 2.2), with five added during later phases of the research. Current research is focused on the original ten catchments. The catchments were well instrumented, with twenty five raingauges located across the ten catchments (Nanni, 1956). The historical raingauges used in the Cathedral Peak research catchments were Snowdon raingauges with Nipher shields as well as Casella Snowdon recording raingauges (Toucher *et al.*, 2016). The Snowdon raingauges with Nipher shields were measured monthly, with this interval decreasing during the higher rainfall periods (Nanni, 1956). These monthly raingauges consisted of a 5 inch orifice, a storage container with a capacity of 10 inches and a surrounding Nipher shield, placed at the same angle as the slope (Nanni, 1956). The current Texas and Davis tipping-bucket raingauges were installed vertically at the same sites as the historical raingauges in the catchments.

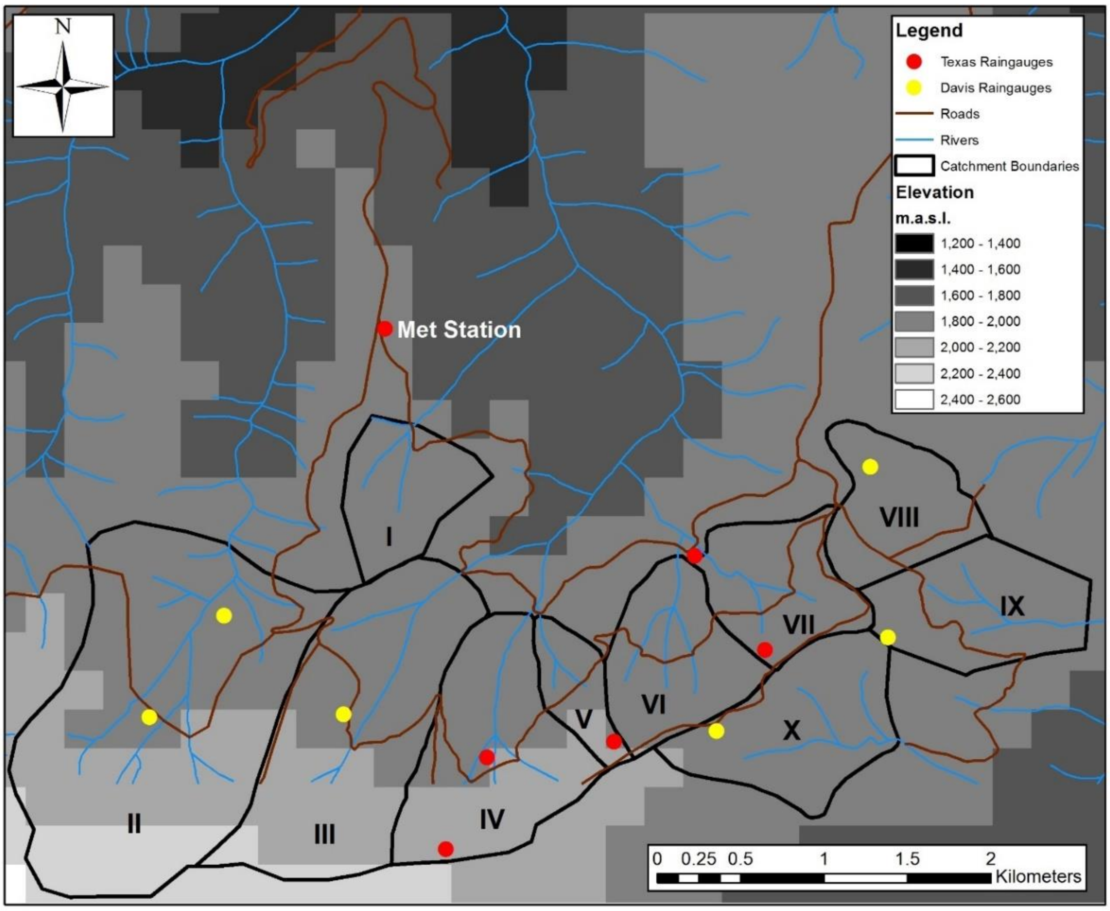

Figure 2.2: Cathedral Peak research catchments indicating the current raingauge sites, comprising Texas high-intensity (Red) and Davis tipping-bucket (Yellow) raingauges. All sites had restored Snowdon gauges.

For this cross-calibration study, 12 raingauge sites (Figure 2.2) where the current gauges have been installed alongside the historical gauges were chosen. Potential sites were evaluated, based on the angle and aspect of the slope, the angle of the raingauge to the slope and the altitude of the site. Sites were selected to cover a range of different altitudes, aspects and slope angles (Table 2.1). A Snowdon replica raingauge was placed into the remaining Nipher shields at each of the 12 sites. The Casella Snowdon recording raingauges could not be restored for the cross-calibration. Paraffin is placed into each raingauge to prevent evaporation during the month as was done previously. The gauges were measured monthly using a measuring cylinder following installation on 22 January 2014. Recording of rainfall from the historical raingauges continued until 07 October 2016. At six sites, towards the end of January 2015 the storage design of the Snowdon raingauges was changed to accommodate a greater volume to prevent overtopping.

Table 2.1: The characteristics of the raingauge sites selected across the Cathedral Peak research catchments

Raingauge Site	Latitude	Longitude	Altitude (m.a.s.l.)	Aspect	Slope Angle (^{o})
Met Station	-28.976	29.236	1866	North	0.0
IIB*	-28.997	29.223	1975	North East	6.0
IIC	-28.991	29.227	1875	North West	5.0
IIIB	-28.996	29.234	1969	East	3.0
IVA	-29.004	29.240	2144	North	29.0
IVB	-28.998	29.241	1960	North	1.0
VA	-28.998	29.248	2068	North West	12.0
VIIA	-28.993	29.257	1976	North West	29.0
VIIC	-28.988	29.252	1849	North West	7.0
VIIIA	-28.983	29.262	1920	South	4.0
IXA	-28.991	29.263	1968	East	21.0
XA	-28.997	29.254	2021	South East	29.0

*The number in front of the letter indicates the catchment in which the site is situated, and the letter indicates its position within the catchments, A for the top of the catchment, B for the middle of the catchment and C for the bottom of the catchment.

2.2.2 Jonkershoek research catchments

The Jonkershoek research catchments (33^{o}57’S; 18^{o}55’E) are located in the Jonkershoek valley to the south-east of Stellenbosch in the Western Cape, South Africa (Scott *et al.*, 2000). The valley has an open end in the north-west and is closed in the South-East by the

Dwarsberg. The mountains which border the Jonkershoek Valley, range in altitude from 792 to 1 525 m.a.s.l. with the Dwarsberg being the highest peak located at the head of the valley (Van Wyk, 1987). Jonkershoek has a Mediterranean-type climate with hot dry summers and wet cold winters. The rainfall predominately occurs during the winter months with the frontal systems moving over the area from the south Atlantic providing the greatest rainfall (SAEON, 2014). About 85 % of the rain falls in the six months from April to September (Scott *et al.*, 1998). The area experiences spatially variable rainfall, with 3 874 mm per annum at Dwarsberg, 1 180 mm per year at the Meteorological station at the bottom centre of the Jonkershoek valley, and only 780 mm per year at Stellenbosch the closest town, located south east of Jonkershoek at a lower altitude (SAEON, 2014).

Recording of rainfall commenced in 1935 (Wicht, 1940) at 15 raingauges located across the Jonkershoek research catchments (Wicht, 1940). The easily accessible gauges were read daily, while the inaccessible gauges were read weekly and monthly (Wicht, 1940). When the raingauges were upgraded to Davis tipping bucket, the Snowdon gauges with Nipher shields at ten sites (Figure 2.3 and Table 2.2) were retained and monitored simultaneously from 27th of June 2011 until the 7th of May 2012.

Table 2.2: The characteristics of the raingauge sites at the Jonkershoek research catchments

Raingauge Site	Latitude	Longitude	Altitude (m.a.s.l.)	Aspect	Slope Angle (°)
7B	-33.971	18.939	278	South West	6.4
8B	-33.987	18.969	366	South East	9.1
9B	-33.979	18.951	292	South West	13.2
11B	-33.958	18.939	400	South West	20.5
12B	-33.972	18.949	337	South West	12.4
13B	-33.975	18.957	439	South West	15
14B	-33.982	18.982	472	South West	14.4
15B	-33.966	18.940	310	West	7.9
19B	-33.976	18.948	298	South East	6.6
20B	-33.988	18.951	409	North East	19.1

2.2.3 Data analysis

The rainfall data from the Cathedral Peak research catchments was collected by the author and the South African Environmental Observation Network (SAEON): Grassland-Wetland-Forest Node. The data from the Jonkershoek research catchments was provided by the SAEON: Fynbos Node. Following data collection, error checking and analysis of the data was undertaken. Initial error checking eliminated obvious poor or unreliable records, for example, periods where the Snowdon's overtopped or the tipping-bucket raingauges malfunctioned. Records from site IVA, Cathedral Peak, were excluded from analysis as the tipping-bucket raingauge proved problematic throughout the research period. Sites 8B and 14B, Jonkershoek, were excluded from the analysis as the orifices of the Snowdon raingauges were stolen following two months of observation.

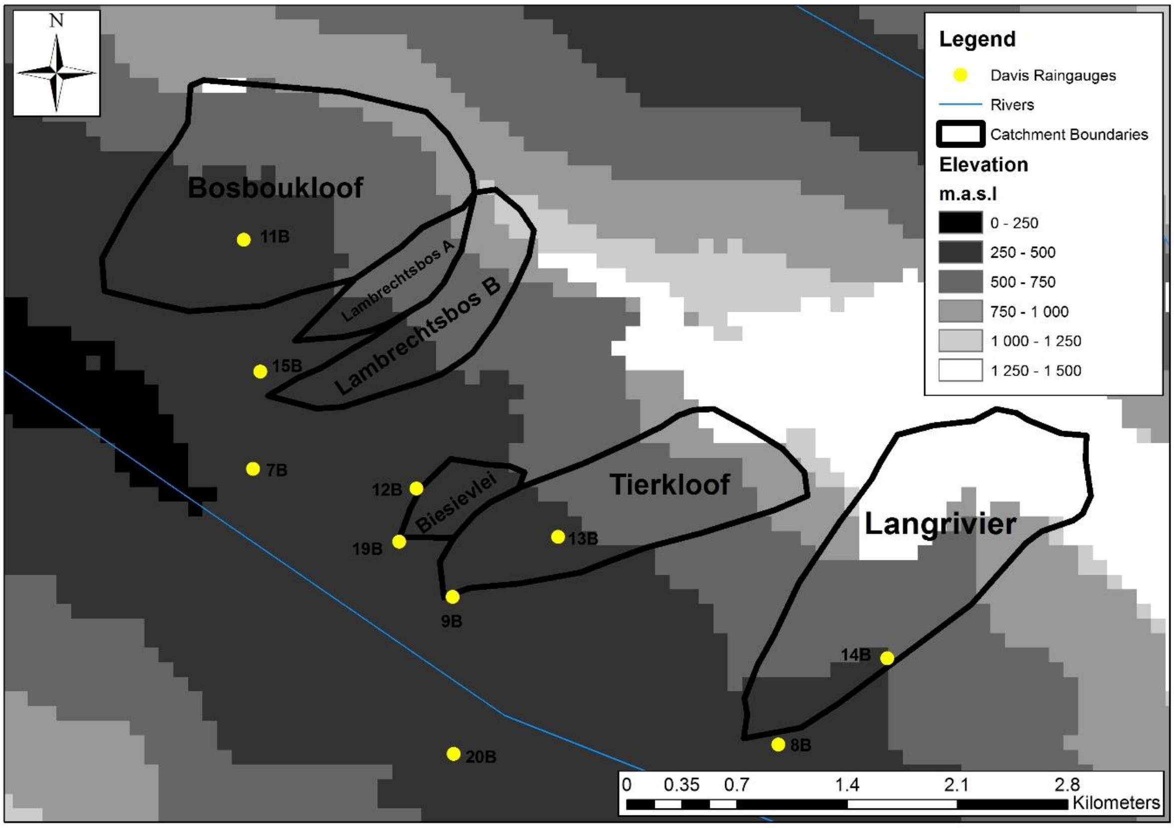

Figure 2.3: Jonkershoek research catchments with the raingauge sites and catchments labelled as of 2012, Davis gauges in same sites as original Snowdon gauges.

The student t-test was selected to determine if there was any statistical difference between the rainfall recorded by the two types of raingauges for each site. When comparing two independent sets of data, the most commonly used statistical test is that of the T test (Helsel and Hirsch, 2002). The student t-test compares "two interdependent groups of data" (Helsel and Hirsch, 2002), in this study, the current and historical raingauges records for the several sites were considered. To conduct the student t-test, it was needed to determine if the data had equal or unequal variance (Helsel and Hirsch, 2002). To determine the variance of the data, an F test was conducted. The data across all sites at both Jonkershoek and Cathedral Peak was determined to have equal variance (Table 2.3). Following the F test, to determine whether the rainfall recorded by the historical and the current raingauges is statistically different or not, the null hypothesis needs to be either rejected or accepted. The null hypothesis for the t-test was $H_0: \mu_x = \mu_\gamma$ where μ_x and μ_γ are the average of the monthly rainfalls recorded by each of the raingauges being compared. The null hypothesis is rejected when $t\,stat > t\,Critical$ and cannot be rejected when $t\,stat < t\,Critical$ (Helsel and Hirsch, 2002). When the null hypothesis was rejected, the statistical difference between the raingauges was significant, and when not rejected, there was no statistically significant difference (Helsel and Hirsch, 2002).

Table 2.3: The outcomes of the F test for equal or unequal variance of the rainfall data from Cathedral Peak and Jonkershoek research catchment sites.

Cathedral Peak research catchments			**Jonkershoek research catchments**		
Site	**Variance**	**P value (α = 0.05)**	**Site**	**Variance**	**P value (α = 0.05)**
Met	Equal	0.483	7B	Equal	0.482
IIB	Equal	0.489	9B	Equal	0.421
IIC	Equal	0.418	11B	Equal	0.359
IIIB	Equal	0.271	12B	Equal	0.490
IVB	Equal	0.426	13B	Equal	0.488
VA	Equal	0.435	15B	Equal	0.435
VIIA	Equal	0.330	19B	Equal	0.497
VIIC	Equal	0.383	20B	Equal	0.434
VIIIA	Equal	0.466			
IXA	Equal	0.346			
XA	Equal	0.415			

2.3 Results

2.3.1 Cathedral Peak research catchments

The relationship between the rainfall measurements of the current and historical raingauges in Cathedral Peak over the research period (January 2014 - October 2016) at a monthly time-step is shown in Figure 2.4. The monthly comparisons over the study period are shown in the appendix as Table A1. To have a fair comparison, the event-based tipping-bucket data was summed to monthly totals matching the historical raingauge measurements before analysis was conducted. Almost no difference was evident between the rainfall recorded by the current and historical raingauges (Figure 2.4), and it was hard to identify which raingauge records more.

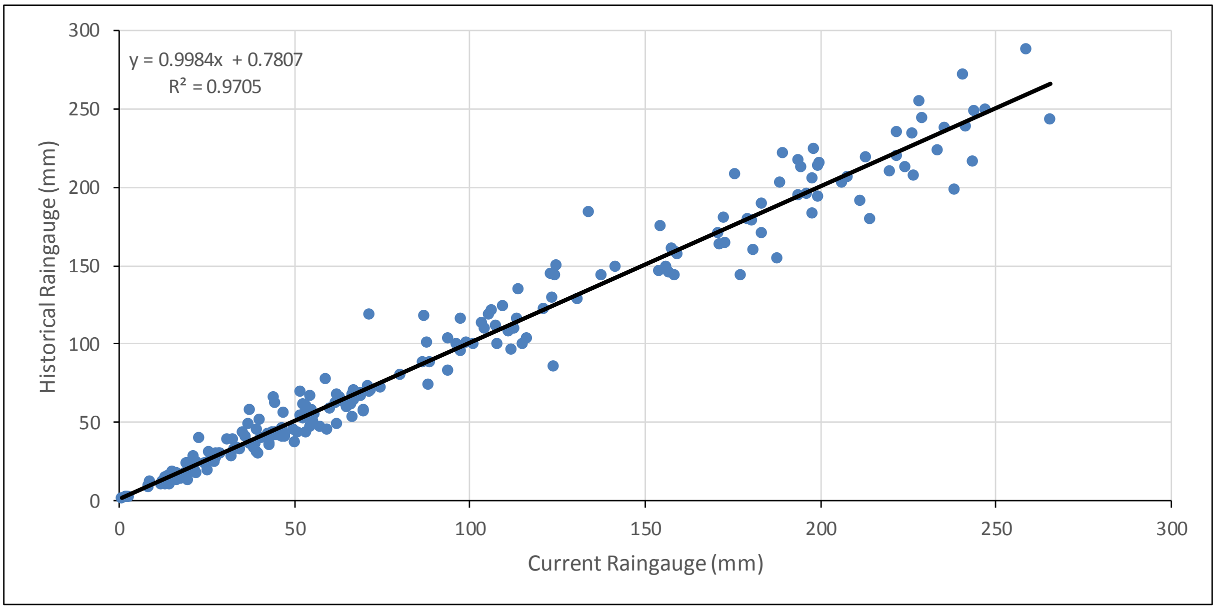

Figure 2.4: A comparison between the rainfall values recorded by all the current and historical raingauges in Cathedral Peak research catchments at a monthly time-step

Furthermore, the statistical T test used shows that there was no statistically significant difference (Table 2.4) between the historical and current raingauges across all sites. Although no statistically significant difference was found between the raingauges, the percentage differences calculated (Table 2.4), show that there were small differences between the raingauges when recording rainfall. A positive value means the current raingauge was recording more rainfall, while a negative value means the historical raingauge was recording more rainfall. This illustrates that there were other factors that could be influencing measurements across the sites. The data was split into wet (January, February, March, October, November and December) and dry (April, May, June, July, August and September) seasons to determine if there was any change in the relationship between the gauges, seasonally. Again, the difference between the raingauges, were determined to be statistically insignificant (Table 2.4).

Table 2.4: The outcomes from the two-sample t-test assuming equal variance for the Cathedral Peak research catchment sites

Site	Statistical Significance	P value (α = 0.05)	% Difference	Dry Season		Wet Season	
				Statistical Significance	P value (α = 0.05)	Statistical Significance	P value (α = 0.05)
Met	Not Significant	0.899	-0.9	Not Significant	0.976	Not Significant	0.963
IIB	Not Significant	0.953	+1.4	Not Significant	0.973	Not Significant	0.948
IIC	Not Significant	0.950	+1.5	Not Significant	0.823	Not Significant	0.996
IIIB	Not Significant	0.761	-7.8	Not Significant	0.931	Not Significant	0.650
IVB	Not Significant	0.685	-13.5	Not Significant	0.613	Not Significant	0.784
VA	Not Significant	0.711	-10.0	Not Significant	0.475	Not Significant	0.705
VIIA	Not Significant	0.955	+1.6	Not Significant	0.808	Not Significant	0.817
VIIC	Not Significant	0.905	-3.2	Not Significant	0.944	Not Significant	0.876
VIIIA	Not Significant	0.977	-1.8	Not Significant	0.998	Not Significant	0.789
IXA	Not Significant	0.673	+10.9	Not Significant	0.721	Not Significant	0.633
XA	Not Significant	0.768	+6.6	Not Significant	0.666	Not Significant	0.764

Differences between gauges may be due to other factors as the differences vary from site to site. To determine whether slope, aspect and current raingauge type of the site has an influence on the difference between the current and historical raingauges, the sites have been ranked in order of their differences between the current and historical raingauges (Table 2.5). Overall, five sites show the current raingauge records the greater rainfall volume, while six sites show the historical raingauge records the greater rainfall volume. The difference either way is never greater than 13.5 %.

From Table 2.5, there was no significant pattern to suggest aspect had an influence. Sites with an East facing aspect, show large differences between the current and historical raingauges. This varies as with site IXA, the current raingauge records 10.9 % more rainfall, while at site IIIB, the current raingauge records 7.8 % less rainfall. At site IVB the current raingauge records 13.5 % less rainfall, and at site VA the current raingauge records 10.0 % less rainfall. Whether this was due to the North aspect is uncertain, with North East and North West aspects showing no significant trend.

Table 2.5: The percentage difference in local rainfall recorded between a current and historical raingauge relative to the current raingauge for sites in Cathedral Peak.

Site	% Difference	Altitude (m.a.s.l)	Aspect	Slope (^{o})	Current Gauge Type
IXA	+10.9	1971	East	21.0	Davis
XA	+6.6	2063	South East	29.0	Davis
VIIA	+1.6	1984	North West	29.0	Texas
IIC	+1.5	1884	North West	5.0	Davis
IIB	+1.4	1988	North East	6.0	Davis
Met Station	-0.9	1871	North	0.0	Texas
VIIIA	-1.8	1924	South East	4.0	Davis
VIIC	-3.2	1850	North West	7.0	Texas
IIIB	-7.8	1969	East	3.0	Davis
VA	-10.0	2063	North West	12.0	Texas
IVB	-13.5	1959	North	1.0	Texas

It appears that for sites with a steep slope (>10°) the current raingauge was recording more rainfall than the historical raingauges at three sites, with site VA being the exception. This may be due to the tilt of the historical raingauges, and was a greater influence when the site is sloped at more than 10°. This occurs across all three sites which make use of both Texas and Davis tipping-bucket raingauges. For sites where the slope is gradual (<10°), the difference between the historical and current raingauges was reduced. Site IIIB and IVB are two exceptions, with a difference of 7.8% and 13.5% respectively. This may not show favour to either the current or historical raingauges, but rather that with an increased slope of the historical raingauge, the difference in rainfall catch between the current and historical raingauges will increase.

It is also important to remember that the historical raingauges are parallel to the slope, and therefore depending on the prevailing weather direction, this can either have a negative or positive effect. For this reason, it is difficult to assign influences to either slope or aspect. In Figure 2.5 the percentage differences have been plotted on a map of the Cathedral Peak research catchments. It is clear how the current raingauges are recording more rainfall on the leeside of the catchments at sites IXA and XA as they are protected from the prevailing weather from the north west. The differences between the raingauges are also a lot greater along the top ridge between catchments IV, V, VI, VII and X, than was found at the lower lying sites in the central and bottom ends of the catchments. Sites IVB and VA show the reverse trend of sites IXA and XA where the historical raingauges are recording more rainfall. This could be due to their exposure to the prevailing weather.

There is a pattern that can be derived from Table 2.5 that suggests that the type of current raingauge used at the site in Cathedral Peak influences the difference recorded between the current and historical raingauges. For sites that used a Davis tipping-bucket raingauge, the Davis tipping-bucket raingauges recorded more rainfall across more sites. For the sites that used the Texas high-intensity raingauges, the historical raingauges recorded more rainfall across more sites. There are a few sites that do not follow the above-mentioned patterns, but these sites are the clear minority. These "minority" sites may have other influences that dominate, such as slope or aspect as mentioned above.

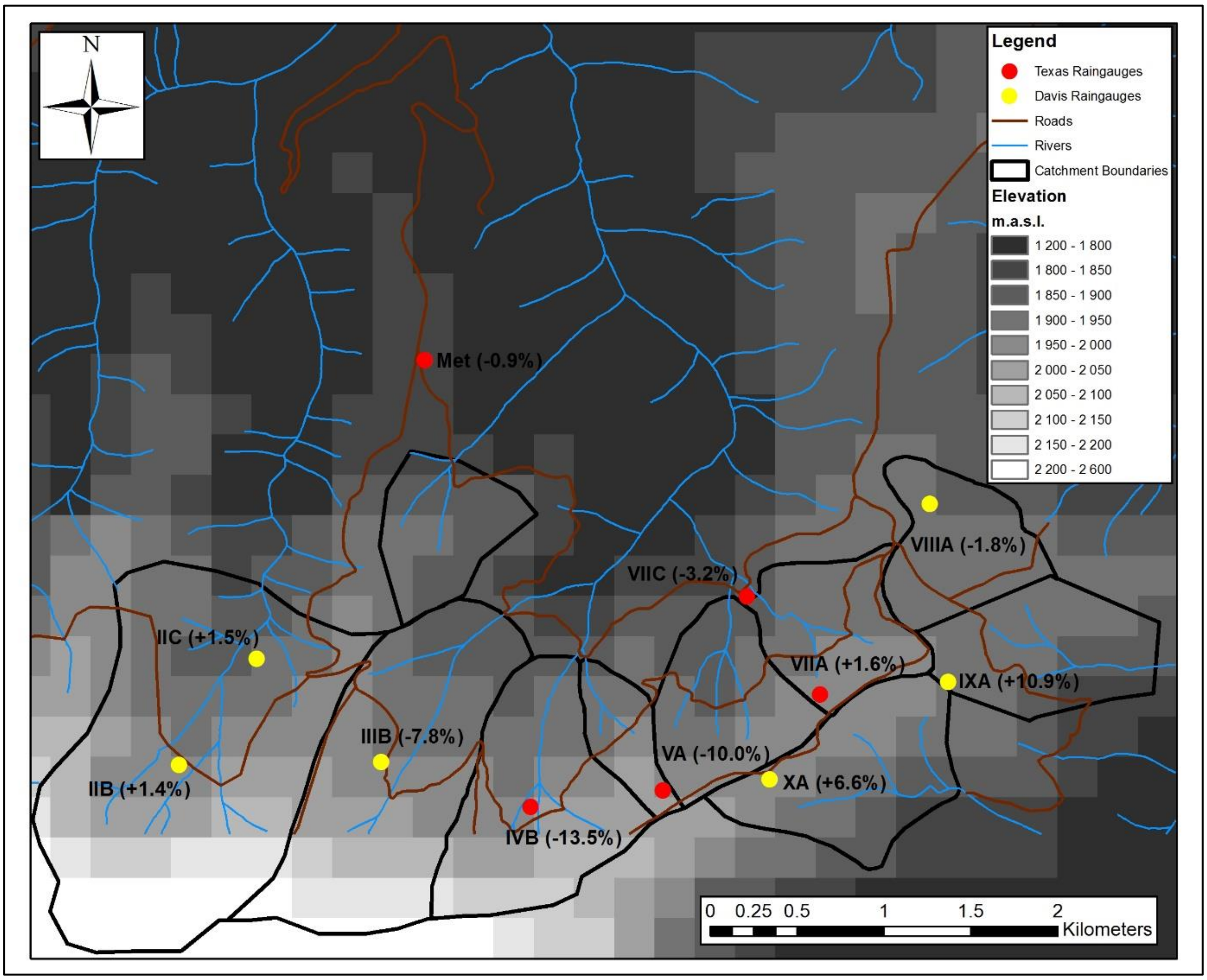

Figure 2.5: Percentage differences between the gauges shown for each site in the Cathedral Peak research catchments

2.3.2 Jonkershoek research catchments

The Jonkershoek Snowdon data was provided in weekly or two week intervals for the observation period of June 2011 to May 2012. This was summed into monthly totals to match the Cathedral Peak data. The monthly comparisons can are shown in the appendix as Table A2. The relationship between the Snowdon and Davis tipping-bucket raingauges shows that for monthly rainfall volumes <40 mm, the Snowdon and Davis raingauges record very similar rainfall (Figure 2.6), while the difference increases in favour of the Snowdon raingauge > 80 mm as the rainfall volume increases.

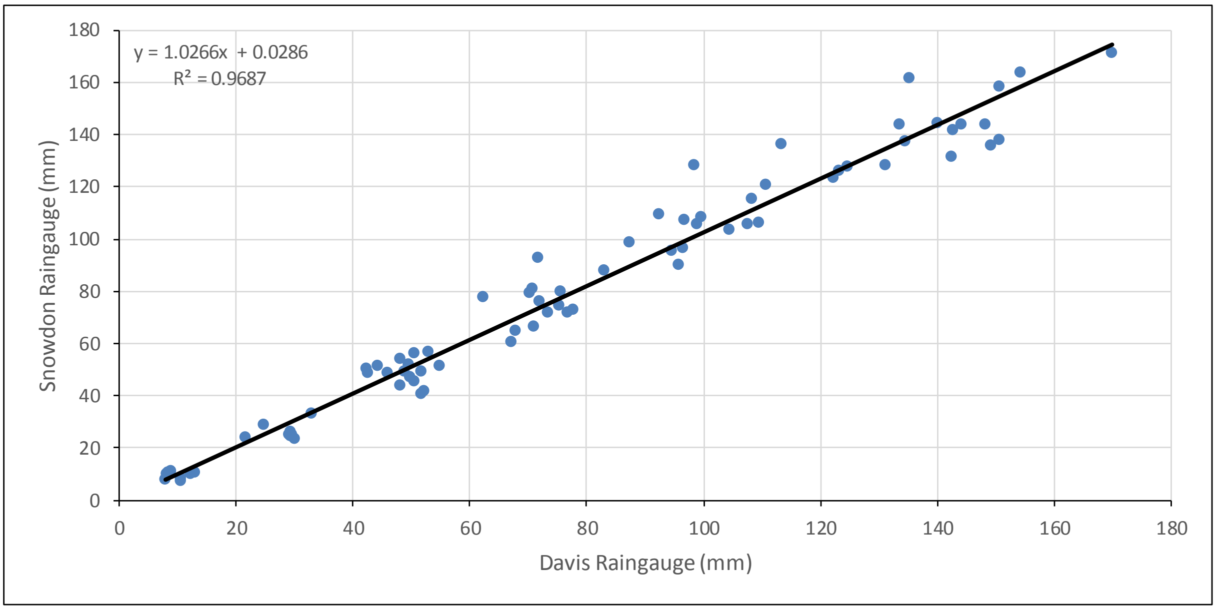

Figure 2.6: A comparison between the Davis and Snowdon raingauges using a monthly time step for all raingauge sites at Jonkershoek

Although there were differences found in the linear regression, statistically it was determined that there were no significant differences between the historical and current raingauges (Table 2.6). Along with the linear regression, the percentage differences between the historical and current raingauges in Jonkershoek show that there were differences between the raingauges, even if these were not statistically significant. Due to the limited observation period, the separation into wet and dry seasons was not possible.

Table 2.6: The outcomes from the two-sample t-test assuming equal variance for the Jonkershoek research catchment sites and the percentage differences between the raingauges, relative to the current raingauge

Site	Statistical Significance	P value ($\alpha = 0.05$)	% Differences
7B	Not Significant	0.905	+3.1
9B	Not Significant	0.736	-9.6
11B	Not Significant	0.877	-3.8
12B	Not Significant	0.955	+1.5
13B	Not Significant	0.702	-11.2
15B	Not Significant	0.884	-4.2
19B	Not Significant	0.873	+4.3
20B	Not Significant	0.763	-12.1

To determine the influence of slope, the sites were ranked in order of their differences between the historical and current raingauges. At four sites, the current raingauge records a higher volume of rainfall than the historical raingauges, by a maximum of 4.3 % at site 19B (Table 2.7). At the remaining four sites, the historical raingauge records a greater volume of rainfall with a maximum difference of 12.1 % at site 20B (Table 2.7). The differences showing the historical raingauge recording greater rainfall volumes, were much larger than the reverse. From Table 2.7, the most evident influence may be that of slope. The percentage differences were mapped for the Jonkershoek research catchments (Figure 2.7). There is a noticeable difference from the head of the valley in the south east where the slopes of the sites are steeper, to the bottom end of the valley in the north west where the slopes are reduced (Figure 2.7). The percentage differences show this, where they are greatest at sites 20B and 13B with differences of 12.1 % and 11.2 % respectively. These two sites are the closest to the head of the valley. Besides the actual slope of the sites, this is more evident based on position in the valley. This is proven by site 11B which is situated on a steep slope, but has a difference of only 3.8 % in favour of the historical raingauge. This may be due to the prevailing weather direction in the valley.

Table 2.7: The percentage difference between a current and historical raingauge relative to the current raingauge for sites in Jonkershoek

Site	% Difference	Altitude (m.a.s.l.)	Aspect	Slope (^{o})	Current Gauge Type
19B	+4.3	298	South East	6.6	Davis
15B	+4.2	310	West	7.9	Davis
7B	+3.1	278	South West	6.4	Davis
12B	+1.5	337	South West	12.4	Davis
11B	-3.8	400	South West	20.5	Davis
9B	-9.6	292	South West	13.2	Davis
13B	-11.2	439	South West	15.0	Davis
20B	-12.1	409	North East	19.1	Davis

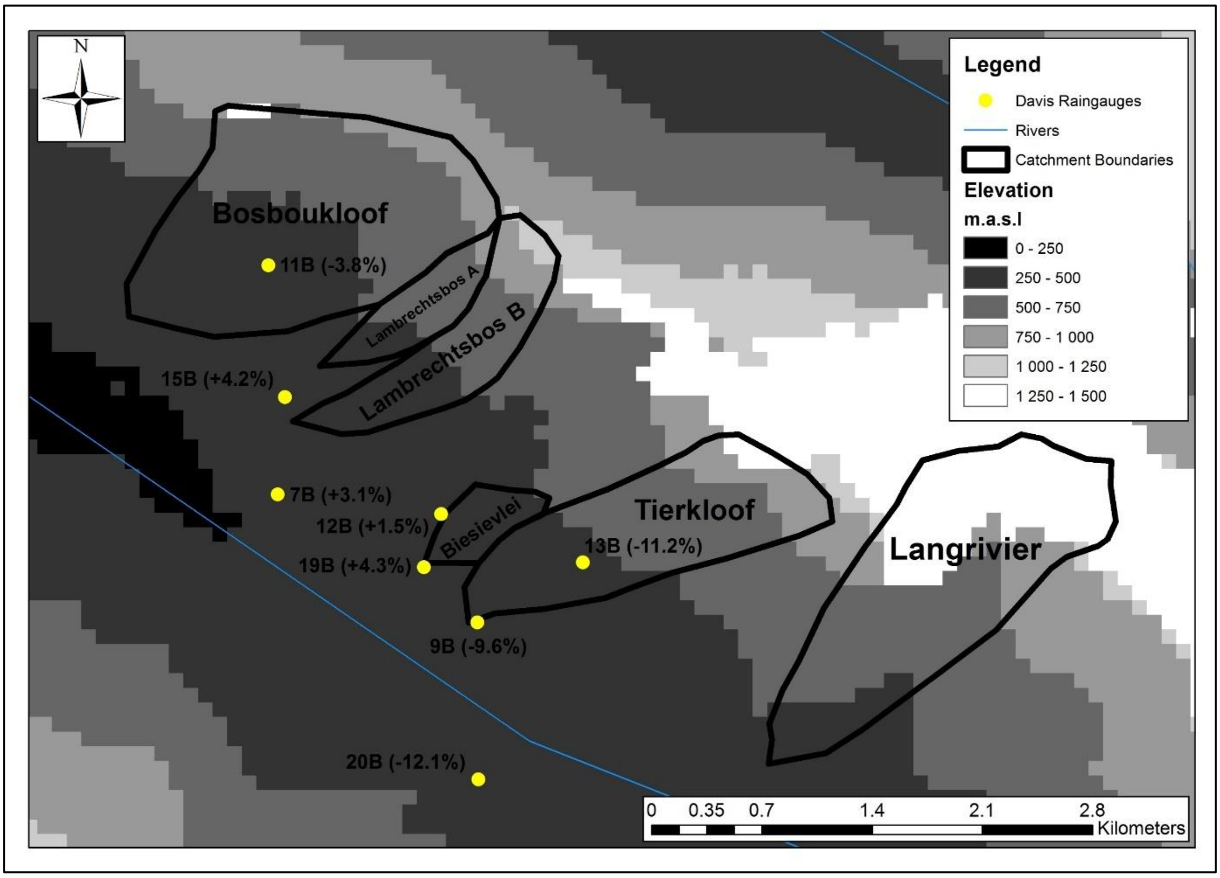

Figure 2.7: Percentage differences between the gauges shown for each site in the Jonkershoek research catchments

2.4 Discussion

Over the 27 months of research in Cathedral Peak and 10 months in Jonkershoek, a general trend where the historical Snowdon gauges measure higher monthly precipitation than the modern gauges, was evident across both catchments. The historical and current raingauges record very similar rainfall volumes, with the difference never exceeding 12.1 % in Jonkershoek and 13.5 % in Cathedral Peak, with the historical raingauge generally recording the greater volume. These percentages are not excessive, as measurement of rainfall by any type of raingauge is susceptible to systematic errors caused by influences such as wind and evaporation. Wind can cause an error upwards of 5%, to as much as 80 % of the rainfall catch (Kurtyka, 1953; Rodda and Dixon, 2012), and evaporation up to 4 % of the rainfall catch (Mekonnen *et al.*, 2014). These two factors combined can cause a greater error then was found between the current and historical raingauges in this study, and this is only considering two types of systematic errors. Statistically the differences between the current raingauge and the historical raingauge were not significant. This finding is contrary to what most literature suggests, i.e. that historical raingauges record more rainfall than current raingauges, across all conditions, due to the differences in design (Molini *et al.*, 2005; Scuito *et al.*, 2009; Colli *et al.*, 2014). As this study was conducted in two high altitude sites, with mountainous terrain, it has provided insight into recording rainfall in these commonly ungauged areas. This is compared to the usual flat land meteorological stations found in other studies. This fact may account for the differences recorded in this study compared to the literature reviewed. Even through the percentage differences between the gauges are statistically insignificant the small differences found need to be understood.

For Cathedral Peak the current and historical raingauges recorded very similar values for both the low and high rainfall months (Figure 2.4). At Jonkershoek (Figure 2.6), the historical raingauges recorded slightly more rainfall for higher rainfall volumes, while there was almost no difference between the raingauges at the lower rainfall volumes. This may illustrate the underestimation of rainfall at the higher volumes by the current raingauges, based on the assumption that higher rainfall volumes were the result of high intensity events. Literature suggests that the current raingauges underestimate rainfall at higher intensities due to the limitations of their mechanisms (Molini *et al.*, 2005; Scuito *et al.*, 2009). As the intensities measured by the historical raingauge cannot be determined, stating that the under recording at higher rainfall volumes by the current raingauges is due to high intensities for this study is an assumption. Literature also states that the errors caused by the mechanisms under-recording at high rainfall intensities are less evident over longer time periods (Molini *et al.*, 2005; Shelton, 2009; Colli *et al.*, 2013). Therefore, this should not be evident at a monthly time step, suggesting other influences. Jonkershoek is located in a winter rainfall region, thus the temperature is lower during the higher rainfall period. Therefore, evaporation, which affects the historical raingauges the most, is reduced as an influence, possibly increasing the difference between the current and historical raingauges during this period. While in Cathedral Peak, evaporation is a considerable influence during the higher rainfall periods being in a summer rainfall region, possibly reducing the difference between the raingauges during this period.

Of the three main physical factors, slope was concluded to have the greatest influence. This may be specific to this comparison, as the historical raingauges were placed at the same angle as the slope, and this varies from site to site. Therefore, a greater slope angle results in a greater difference between the orifice angles of the current and historical raingauges. From the results, it could be suggested that with an increase in slope angle, there is an increasing difference in rainfall recorded between the current and historical raingauges. This was evident at both Cathedral Peak and Jonkershoek. In Cathedral Peak, a slope angle of more than 10° showed sites having a greater difference in rainfall recorded. For sites with a slope of less than 10° the difference between the historical and current raingauges is not greater than 3.2 %, besides IIIB and IVB. This may suggest that when level, both raingauges perform similarly to each other. The same pattern was evident in Jonkershoek, where raingauges with a slope of more than 10^{o} showed greater differences between the current and historical raingauges. It also showed that when sites were sloped more than 10° the historical raingauges would record more rainfall. This was true for four out of five sites, with the greatest difference being -12.1% at site 20B. At all sites with a slope of less than 10°, the current raingauges recorded more rainfall, but by a smaller difference, with the greatest being +4.3 % at site 9B. This may have been a clearer, had the observation period been longer. Thus, it is still uncertain whether slope results in the historical or the current raingauge recording more rainfall. What is clearer, is that with an increase in slope, the difference in rainfall totals between the raingauges, are more likely to increase, as this occurred at both Cathedral Peak and Jonkershoek. This finding is consistent with literature, which states that vertical raingauges are sufficient and accurate in flat lands, but provide errors when used in areas with significant topography and relief (Hamilton, 1954).

Aside from slope, there is little evidence to suggest that altitude or aspect have any influence on the relationship between the historical and current raingauges in Cathedral Peak and Jonkershoek. What may be suggested, is that aspect can have an influence when combined with slope. Sites IXA and XA in Cathedral Peak both have an uncommon aspect. Although site VIIIA had the same aspect as site IXA, their respective catchments and exposure to the elements were very different. Raingauges IXA and XA were on the leeside of the Cathedral Peak catchments, sheltered from the prevailing wind from the north west. This is very evident upon a site visit, though not clear in Figure 2.2 and 2.5. This may be the explanation for the larger differences found at these sites, where the current raingauge was recording more rainfall. Site IVB and VA which are on the windward side of the slope and facing the prevailing weather, at a similar location and altitude to the other two sites show the reverse pattern. As the prevailing wind is from the north west, wind blows up the slope at catchment IV and V and down the slope of catchments IX and X. Morris *et al.* (2016) found a strong rainfall gradient from west to east, especially in the wet season for the Cathedral Peak region. This reinforces the exposure of sites IVB and VA to the prevailing weather compared to sites IXA and XA. This could result in the current raingauges, which are placed level with the horizon, to record less rainfall at IVB and VA with the upslope wind, and more rainfall at IXA and XA with the downslope wind, as the historical raingauges are sloped. Therefore, with a downslope wind they are expected to under-record, while with an upslope wind they are expected to over-record. This is consistent with literature, which states that the differences between the vertical and tilted raingauges is greatest when the site faces the prevailing weather, and under recording may occur when the dominant wind direction is downslope (Hamilton, 1954; Ward and Robinson, 2000).

In Jonkershoek, location within the valley may be more important than slope. It is evident that in the valley, from the south east to the north west, the differences between the raingauges decreases (Figure 2.7). The greater differences at the south-east end of the valley show the historical raingauge recording more rainfall. As Jonkershoek has a unique valley shape, this may be causing this pattern, due to the manner in which the weather interacts with the valley. If sites 8B and 14B in the Langrivier catchment had been able to record over this period, it may have helped to show this more clearly.

As well as the physical and topographical features, current raingauge design was an important factor in this study. In Cathedral Peak, Texas high-intensity and Davis tipping-bucket raingauges were used. When comparing the two types of current raingauges to the historical, differences in favour of either one or another were expected. In Cathedral Peak, all but one of the current raingauges that recorded more rainfall than the historical raingauges were Davis, while of the raingauges that recorded less, two were Davis. Site IIIB again, did not follow this relationship, possibly suggesting other dominant influences. From Cathedral Peak, it was clear that the majority of the Texas raingauges recorded less rainfall than the historical raingauges, while the majority of Davis raingauges recorded more. The sites that showed the reverse occurring be due to other dominant influences, mentioned above, acting at those sites, such as slope or aspect. The influence of the Nipher shield on the historical raingauges against the unshielded tipping-bucket raingauges was hard to determine with the monthly time step. There is no clear pattern that can be attributed to the Nipher shield.

The main aim of the study was to determine correction factors that can be applied to either the historical or current rainfall records in order to create a consistent rainfall record that can be used for the monitoring of global change. Based on the finding that the differences between the historical and current raingauges are not statistically significant and there is no clear relationship between the percentage differences and various factors, there is no need for the application of correction factors. The current raingauges are similar enough to the historical raingauges to continue the rainfall record without affecting the homogeneity and allow for the monitoring of global change in the Cathedral Peak and Jonkershoek research catchments.

2.5 Conclusion

With the decreasing number of raingauges in South Africa, the importance of long term monitoring sites such as Cathedral Peak and Jonkershoek has grown. Furthermore, the conservation of the homogeneity of their long-term data sets is just as important. Cathedral Peak and Jonkershoek are also important high altitude catchments that provide insight into rainfall measurement in important streamflow generating areas of South Africa, where the gauging networks are sparse. With the growing focus on global change monitoring, continuous recording of data at both Cathedral Peak and Jonkershoek is essential. Based on 27 months of the Cathedral Peak study and the 10 months of the Jonkershoek study, some important conclusions can be made. The historical and current raingauges record very similar rainfall volumes across high and low rainfalls at a monthly time step. The differences between the raingauges are not statistically significant. Due to the small differences between the raingauges, there is no requirement for the use of correction factors, as they may be more of a hindrance than an advantage. With the short time frame for this study, as well as the limited conditions, it was hard to determine the influence of aspect and slope on the rainfall catch difference between the raingauges. The interesting outcome was that of slope, which could have developed a more defined pattern had a longer study period been available. It is evident that there could be a link to an increasing difference between the current and historical raingauges with an increasing slope angle. Slope and aspect have also been found to act together, with evidence at selected sites in Cathedral Peak and along the valley profile of Jonkershoek. Having used both current raingauge types at Cathedral Peak, it is shown that the Davis raingauges record more, while the Texas raingauges record less rainfall than the historical raingauges. The influence of the Nipher shield was difficult to determine from monthly data. Event data at a smaller time step would provide better insight into the influence of the Nipher shield. The recommendations from this study are that the influence of the Nipher shield be investigated as well as the differences in rainfall measurement using the Davis and Texas tipping bucket gauges.

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Lead into Chapter 3

From chapter 2, it was concluded that there was no significant difference between the measurements from the historical and current raingauges considering aspect and slope. Therefore, by removing their influence, chapter 3 focuses on the third objective, to determine the influence of raingauge shielding and design in mountainous areas. The influence of event characteristics such as wind speed, duration, intensity and depth are considered. A monthly comparison between the Snowdon historical raingauge and a shielded and unshielded Texas raingauge, against the reference ground level raingauge is also analysed.

CHAPTER 3: INVESTIGATION INTO THE ACCURACY OF MODERN TEXAS HIGH INTENSITY RAINGAUGES AT A HIGH ALTITUDE METEOROLOGICAL STATION IN CATHEDRAL PEAK

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ABSTRACT

The tipping-bucket raingauge, has generally replaced the historical manual raingauges, such as the popular Snowdon raingauge, in rainfall monitoring networks worldwide. The accuracy of rainfall volumes captured by current tipping-bucket raingauges is a topical debate in hydrology and meteorology. As the Snowdon raingauges were used historically in the Cathedral Peak research catchments with Nipher shields, the meteorological station provided an ideal site to conduct a comparison between the Snowdon and Texas tipping-bucket raingauges, as well as to test the influence of shielding the current Texas raingauges at the site. The overall aim of this study was to improve the understanding of the influence of a shield and gauge design on rainfall measurement accuracy. A ground level raingauge was used as a reference to compare to the above ground raingauges. After 20 months of observation, the comparison between the Snowdon raingauge and the Texas raingauge showed that there was little difference between the gauges, with the Snowdon raingauge recording 0.7 % more rainfall, and both raingauges recording 7.2 % and 7.9 % less rainfall than the ground level raingauge. The shielded Texas raingauge recorded the least amount of rainfall compared to the other raingauges, and recorded 12 % less than the ground level raingauge when analysed at a monthly time step. From 176 rainfall events, the unshielded Texas raingauge recorded more rainfall than the shielded Texas raingauge for 52.27 % of the events, while the shielded Texas raingauge recorded more rainfall for only 14.20 % of the events. For 33.52 % of the events there was no difference between the raingauges. The difference between the shielded and unshielded raingauges is greatest for high intensity, low wind speed events.

3.1 Introduction

The accuracy of rainfall measurements, and rainfall intensity volumes captured by current tipping-bucket raingauges is a popular debate in hydrology and meteorology as well as the differences between types and makes of tipping-bucket raingauges (Lanza and Vuerich, 2012). The tipping-bucket raingauge, has generally replaced the historical manual raingauges, such as the popular Snowdon raingauge, in rainfall monitoring networks worldwide (Molini *et al.*, 2001; Strangeways, 2010; Tapiador *et al.*, 2012). The reasons for the increased popularity of the tipping-bucket raingauge include being automated and providing a better temporal measurement resolution. However questions still remain about the accuracy of its representation of actual rainfall (Upton and Rahimi, 2003; Savina *et al.*, 2012; Mekonnen *et al.*, 2014).

Rainfall can be considered as the simplest hydrological component to measure, however, it is difficult to measure accurately (Davie, 2003). By reducing the errors, a closer representation of the natural system can be achieved. The errors in rainfall measurement are the result of natural factors such as wind, evaporation and temperature (Michelson, 2004; Colli *et al.*, 2014). In rainfall measurement, both systematic and random errors occur (Tokay *et al.*, 2003; Mekonnen *et al.*, 2014). Systematic errors which occur during the recording of rainfall are mainly the result of wind and its influence over the orifice of the raingauge (Michelson, 2004; Sugiura *et al.*, 2006; Mekonnen *et al.*, 2014). According to the WMO (2008), wind has the greatest influence on the rainfall catch of a raingauge (Michelson, 2004; Devine and Mekis, 2008). There are two effects of wind to focus on. The effect of the raingauge as an obstruction to the flow of wind, and the effect of the landscape and site on wind flow (Green, 1970; Dreaver and Hutchinson, 1974; De Villiers, 1990; WMO, 2008). Wind is turbulent and non-uniform over the earth’s surface (Strangeways, 2004), thus when wind approaches the raingauge it may alter its path and take several paths around the raingauge, causing a disturbed airflow over the orifice (Strangeways, 2004). This can result in a 35% increase in the speed of the wind over the orifice of the raingauge (Devine and Mekis, 2008).

The underestimation of rainfall due to wind is determined by two factors, the wind speed and the raindrop diameter (Davie, 2003). Chvíla *et al.* (2005) found that there is a difference between under-catch, due to wind during convective precipitation, and non-convective precipitation, with the non-convective precipitation creating the greater error. With a smaller rain drop diameter, the effects of wind on rainfall readings increase (Chvíla *et al.*, 2005). Convective rainfall events tend to have a larger rain drop diameter than non-convective rainfall events, with the same intensity (Chvíla *et al.*, 2005). Chvíla *et al.* (2005) also found that the error created by wind, increased with an increasing wind speed and decreasing rainfall intensity. This is again as a result of rain drop diameter which decreases with a decreasing intensity. The effect of wind is greater for snow, than liquid forms of precipitation (Chang, 2006).

A method introduced to reduce the influence of wind on rainfall catch, is to use a form of shield. Several studies (e.g. Larson, 1971; Neff, 1977; Chang and Flanneiy, 1998; Sugiura *et al.*, 2006) have shown that a shield results in a greater rainfall catch, but the increase in catch may not be as significant as expected. Seibert and Morén (1999) found that the raingauge shield had the greatest influence during low intensity rainfall events with high wind speeds. While for rainfall events with a high intensity, the shield had little effect. De Villiers (1990) found that when the orifice was placed lower than the top of the shield, it resulted in small eddy currents occurring within the shield, thus an under-catch by the raingauge occurred.

Besides the influence of wind on rainfall catch, the design of the raingauge also has a substantial influence on the rainfall measurement. Historically in Cathedral Peak, Snowdon raingauges with Nipher shields were used to record monthly rainfall from 1949 to 1995 when funding came to an end (Everson *et al*., 1998; Toucher *et al*., 2016). In 2012, monitoring at Cathedral Peak was re-established, however, for the current period of research Texas high-intensity and Davis tipping-bucket raingauges were installed, replacing the Snowdon raingauges. The Snowdon raingauge is considered to provide a good representation of the actual rainfall occurring (Burt, 2013). The Nipher shield is believed to create a smooth air flow over the orifice of the raingauge, with similar speed and characteristics to wind in an open field (Devine and Mekis, 2008). Being a manual raingauge, the Snowdon raingauge has a storage container, which is designed to reduce the effects of evaporation between measurement periods (WMO, 2008). Beyond this, it is common practice to add a set volume of “oil” to the storage container to create a barrier between the stored rainfall and evaporation surface (WMO, 2008). The measurement method for manual raingauges is highly susceptible to human error and is dependent on the resolution of the apparatus used (Devine and Mekis, 2008). On the other hand, tipping-bucket raingauges are automated and event based, providing rainfall intensity information (Habib *et al.*, 2001; Chang, 2006). Although they provide better resolution measurements, tipping-bucket raingauges are often considered to underestimate the rainfall occurring (Molini *et al.*, 2005; Colli *et al.*, 2014). Underestimation increases with an increasing rainfall intensity due to the limitations of the tipping bucket mechanism (Molini *et al.*, 2005; Scuito *et al.*, 2009). Additionally, high intensity rainfall can cause the mechanism to seize (Ward and Robinson, 2000). With light intensity rainfall, water may also remain in the bucket exposing it to evaporation before it can be recorded (Habib *et al.*, 2001). Tipping-bucket mechanisms are sensitive to small disturbances, which can trigger the bucket to tip when there is no rainfall occurring (Scuito *et al.*, 2009), as well as the blocking of the orifice from natural sources (Steiner *et al.*, 1999; Upton, 2002). Automatic raingauges use dataloggers which may become corrupt, or lose power resulting in a loss of data (Scuito *et al.*, 2009). Upton and Rahimi (2003) found in their study of 22 raingauges, that 14 of them experienced a form of data transfer or electronic problem. This illustrates the common nature of this problem. As tipping-bucket raingauges are mechanical in nature, maintenance plays an important part in reducing the errors in rainfall measurement (Tapiador *et al.*, 2012). Tipping-bucket raingauges typically do not have shields placed around them (Devine and Mekis, 2008).

When comparing a tipping-bucket raingauge and manual raingauge, there needs to be a reference raingauge. The World Meteorological Organisation (2008) suggests a ground level raingauge as a reference raingauge, as due to their reduced wind effects, they provide the most accurate measurement of rainfall (Dreaver and Hutchinson, 1974; Chang, 2006; Rodda and Dixon, 2012; Mekonnen *et al.*, 2014). Several studies have investigated the difference between ground level raingauges and above ground raingauges with various scenarios. Sevruk *et al.* (2009) considered the differences between various national raingauges and that of a Snowdon raingauge in a pit at ground level. From this research, it was concluded that the pit raingauge recorded more rainfall. The losses from the standard raingauges were attributed to wind effects and wetting and evaporation losses (Sevruk *et al.*, 2009). The influence and losses due to wind, were dependent on the type of raingauge, the speed of the wind as well as the rainfall intensity (Sevruk *et al.*, 2009). These losses were determined to be on average 3% and higher, if evaporation and wetting losses are taken into consideration (Sevruk *et al.*, 2009).

Duchon and Essenberg (2001) compared tipping bucket raingauges with and without shields as well as gauges sited in pits. They used an Alter shield, which was designed in 1937 by

Cecil Alter, and is different from the Nipher shield in that it is not solid and consists of hanging slats which make up the shield, preventing the build-up of snow within the shield (Strangeways, 2010). When comparing the unshielded tipping-bucket raingauge above ground, against the pit tipping-bucket raingauge, for 101 rainfall events, they found that the above ground gauge underestimated rainfall by 4 % (Duchon and Essenberg, 2001). This value increased drastically for a single rainfall event with a high wind speed and intensity, resulting in a 15 % underestimation for the non-shielded, and a 12 % underestimate for the shielded raingauge against the pit gauge. Another focus of the study was to understand the influence of the Alter shield between the two-above ground raingauge scenarios. Results indicated that the effect of the shield resulted in, on average, a 1 % increase in rainfall catch. However, with the above-mentioned extreme event, the increase in catch was 3 % (Duchon and Essenberg, 2001). This study illustrated the importance and accuracy of the pit raingauge and the minor influence of a shield when using tipping-bucket raingauges.

Historically the Snowdon raingauges were used with Nipher shields in the Cathedral Peak research catchments, as it was believed that they improved the rainfall catch. With the transition to tipping-bucket raingauges across most monitoring networks, there is a need to determine the benefits of shielding the rainfall catch of tipping-bucket raingauges, and determine whether it is necessary. Therefore, the aim of this study was to improve the understanding of the influence of a shield and gauge design on rainfall measurement accuracy. To achieve this aim, a Snowdon historical raingauge with Nipher shield and a Texas tipping-bucket raingauge with and without a Nipher shield were compared to rainfall measurements obtained using a ground level raingauge. A further objective was to determine the differences in rainfall measurement between the historical Snowdon raingauge with Nipher shield and the Texas tipping-bucket raingauge, and to determine which is the most accurate, taking the ground level gauge as the reference. The final objective of this study is to improve the understanding of the influence of the wind shield on the rainfall measurements and based on the results, make recommendations on whether or not shields should be used in research raingauge networks to improve accuracy.

3.2 Methodology

3.2.1 Cathedral Peak research catchments

The location for this study is the meteorological station (28°58’32.12”S; 29°14’8.70”E) referred to as Mike’s Pass meteorological station near the Cathedral Peak research catchments (Figure 3.1).

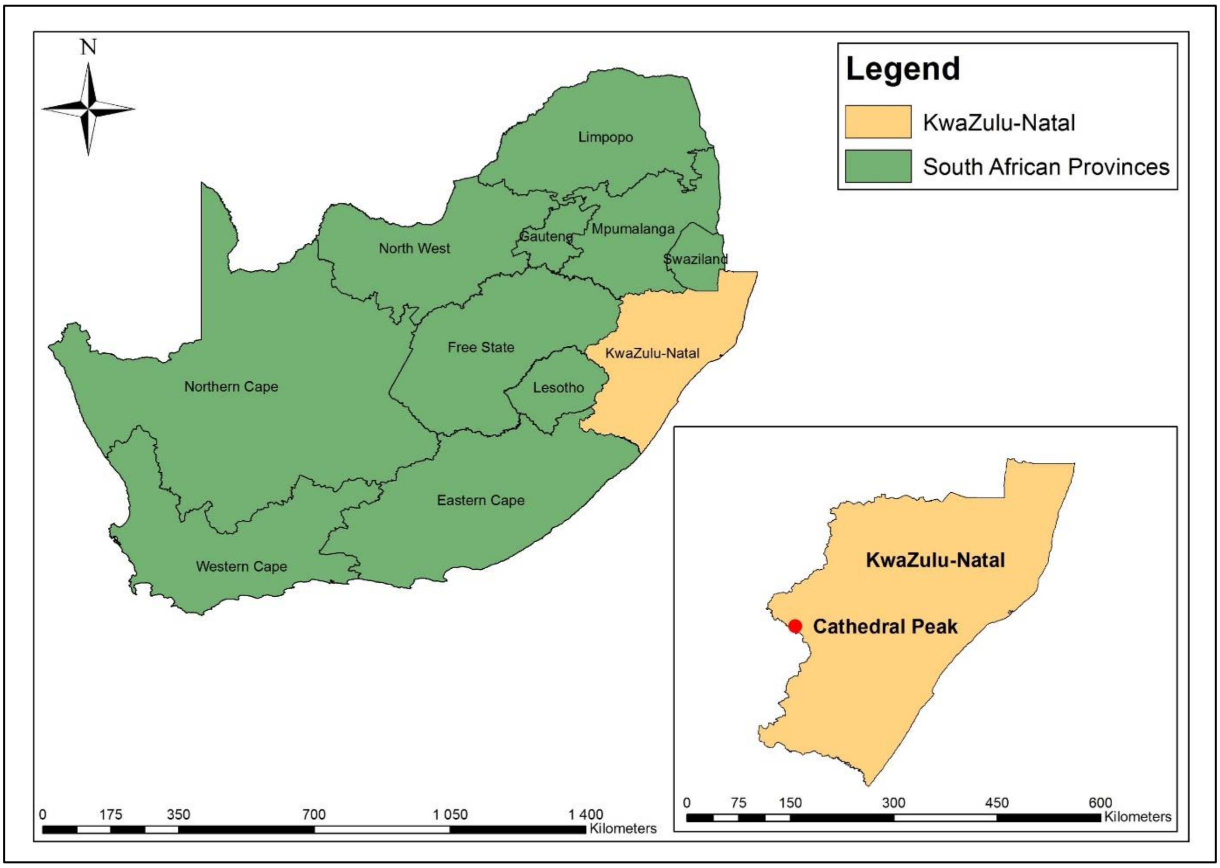


Figure 3.1: The location of the Mikes Pass Meteorological station near the Cathedral Peak research catchments in KwaZulu-Natal, South Africa.

The Cathedral Peak research catchments are located in the Drakensberg mountain range, KwaZulu-Natal, South Africa (Nanni, 1956). The mean annual precipitation (MAP) for the site is approximately 1 400 mm per annum (Bosch, 1979). Most of the precipitation occurs during the summer period, as localised thunderstorms, with most rainfall occurring during January (Nanni, 1956). In the winter, the area experiences occasional long duration, low intensity frontal events (Nel and Sumner, 2006 (the berg article)). The meteorological station was established in 1948, and consisted of several meteorological instruments which were measured daily at a set time of 08H00 (Nanni, 1956). The site, after re-establishment in 2012, consists of the remnants of the historical equipment, and a newly installed automatic weather station (AWS). The AWS consists of a wind vane with anemometer which provides wind speed and direction data, a pyranometer providing solar radiation data, a thermometer providing air temperature data, and a fog gauge and Texas tipping-bucket raingauge. A Snowdon replica raingauge was placed into the remaining Nipher shield at the Meteorological station in February 2014. In January 2015, two further additions were made, a Texas tipping-bucket raingauge was placed inside of an additional Nipher shield brought up to the site, as well as the installation of a ground level raingauge with a Texas tipping-bucket raingauge. The current layout of the meteorological station can be seen in Figure 3.2.

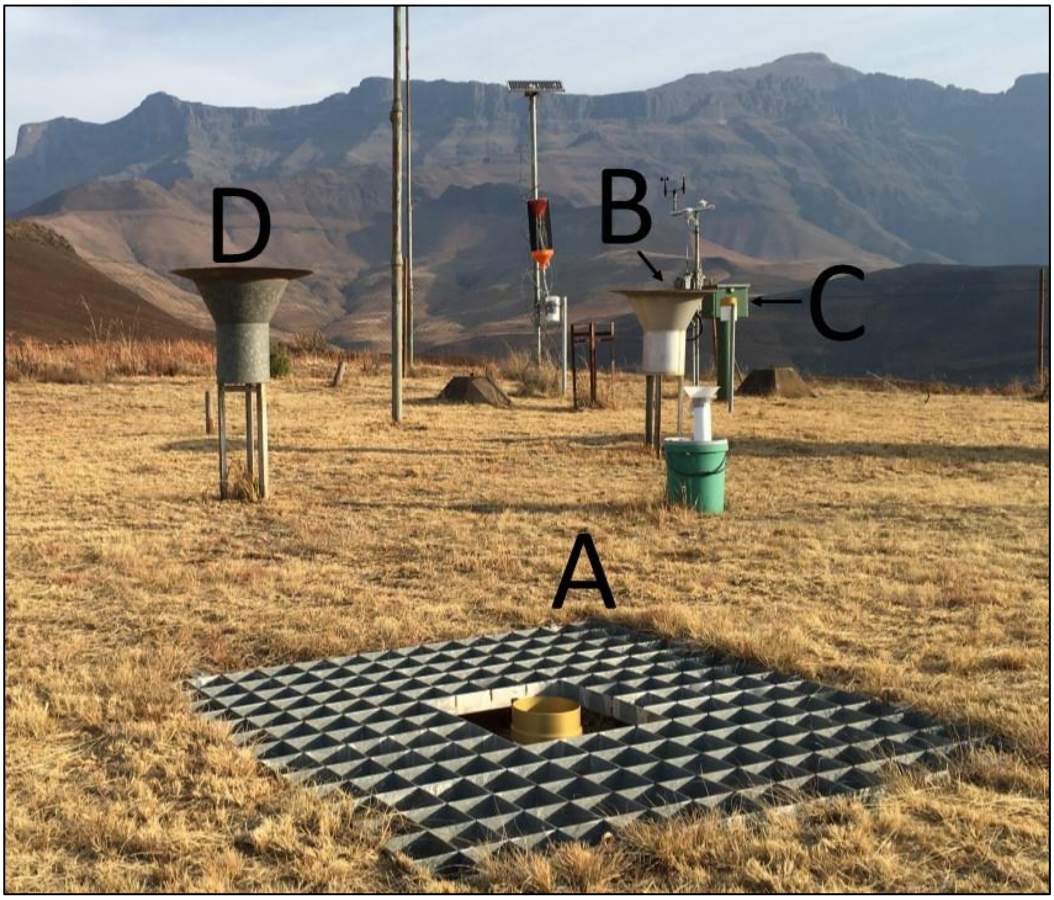


Figure 3.2: The current layout of the Meteorological Station at the entrance to the Cathedral Peak research catchments with gauges labelled (A: Ground level, B: Snowdon raingauge, C: Texas high-intensity raingauge, D: Texas high-intensity raingauge shielded)

3.2.2 Equipment

The Snowdon raingauge used for this study was a replica. It consisted of a standard 5 inch raingauge orifice with a storage container. To reduce the influence of evaporation, paraffin was added to the storage container after each measurement. The Snowdon raingauge was used historically with a Nipher shield, and the replica was placed into a metal frame that fitted into the remaining Nipher shield at the Meteorological station. The Nipher shield is similar in shape to an "inverted cone" and is used to bend the wind around the raingauge in such a way that the air directly above the orifice is undisturbed (De Villiers, 1990; Duchon and Essenberg, 2001). The Nipher shield's inverted cone shape is designed to force the wind downward away from the orifice (De Villiers, 1990; Devine and Mekis, 2008). The first of the automatic tipping bucket raingauges used was a Texas Electronics (TE525) high intensity raingauge connected to the AWS. Each tip records 0.254 mm of rainfall. This was checked through a calibration in the laboratory before installation at the site. The rainfall data is recorded and stored on a datalogger (CR1000, Campbell Scientific Inc., Logan, Utah, USA) (Toucher *et al.*, 2016). Another Texas tipping-bucket raingauge used for this study was placed in a similar metal frame as the Snowdon replica raingauge to fit it into the Nipher shield. This Nipher shield was added to the site following the decision to place a Texas raingauge in a shield to determine the influence of the Nipher shield. The final Texas tipping-bucket raingauge used was for the ground level raingauge. The ground level raingauge was designed according to the World Meteorological specifications (WMO, 2008). A metal grid that is 1.2 m by 1.2 m wide was manufactured. In the centre, a square in the grid was left open to accommodate the Texas tipping-bucket raingauge which was placed on a pole in the centre of the pit. Before the grid was installed, a 0.5 m deep pit was dug. The Texas raingauge is placed into this pit so that its orifice is level with the surrounding ground and grid. The grid is used to prevent in-splash into the orifice, as well as to decrease the effects of the wind around the orifice (WMO, 2008; Mekonnen *et al.*, 2014). An alternative to the metal grid is that of a mat that surrounds the orifice of the gauge and is used to prevent in-splash into the raingauge without the need for a pit (Dreaver and Hutchinson, 1974). The Texas tipping-bucket raingauges used in the ground level and Nipher shield, use the Onset HOBO™ Pendent Event Datalogger (UA-003-64) that is connected to the raingauge mechanism. Data is downloaded from this pendent using a shuttle.

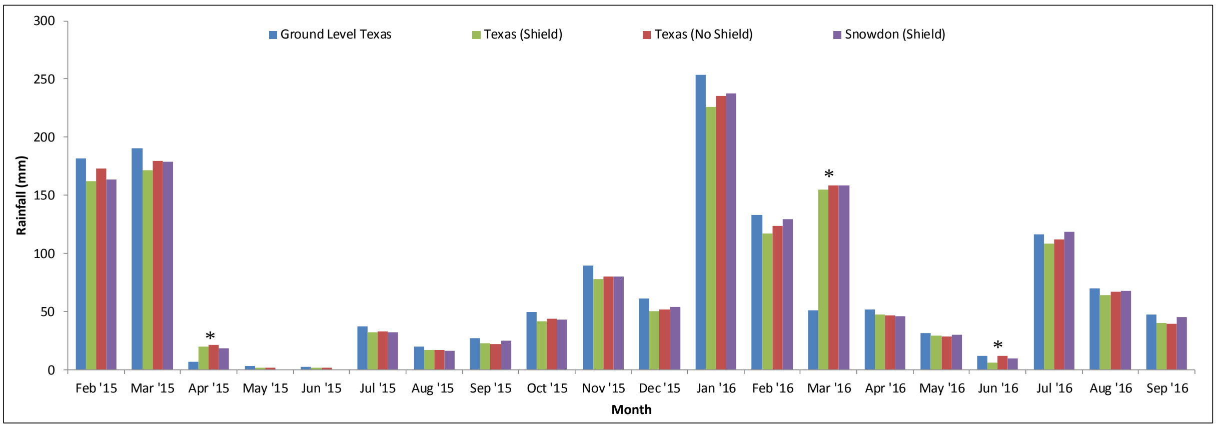
3.2.3 Data Analysis

The rainfall data from the Cathedral Peak Meteorological station was collected by the author and the South African Environmental Observation Network (SAEON): Grassland Node over the observation period from February 2015 to September 2016. Following data collection and error checking, an analysis of the data was undertaken. To understand the relationship between the raingauges and the ground level raingauge, rainfall events were identified. These were selected based on rainfall volume and duration. For an event to have occurred, at least 1 mm of rainfall needed to have been recorded, with the end of the event marked by a period of 2 hours with no rainfall. Wind speed data was obtained from the AWS for these events. The rainfall was summed into 5 min intervals from the shielded Texas and the ground level Texas to match the rainfall measured by the unshielded Texas raingauge connected to the AWS. In total, 176 events were identified from the 20 months of observation, where all three tipping-bucket raingauges were working correctly. These varied from short duration, high intensity storm events to long duration, low intensity frontal events, characteristic of the weather systems acting in the area. It is important to represent the different rainfall mechanisms acting in the area, as the relationship between the raingauges may be very different for convective and frontal events. A regression analysis was conducted on the data to determine the influence of the main characteristics of rainfall events. The characteristics selected were: duration of the event, rainfall depth of the event, the average intensity of the event, as well as the peak and average wind speed of the event.

3.3 Results

3.3.1 Analysis of monthly rainfall measurements

Initially the data was considered at a monthly time step in order to accommodate the historical Snowdon raingauge which is only measured monthly. A comparison of the rainfall recorded by all four of the raingauges over the entire observation period (February 2015 to September 2016) is shown in Figure 3.3.



*indicates that at least one of the four raingauges malfunctioned during the month

Figure 3.3: A comparison between the four different raingauges used at the Meteorological station in the Cathedral Peak research catchments over the period of observation

From Figure 3.3 it is evident that across all months, the ground level consistently records the most rainfall. This is followed by either the Snowdon raingauge or the unshielded Texas raingauge. The difference between the three other raingauges and the ground level raingauge, increases with an increase in rainfall. The shielded Texas raingauge records the least amount of rainfall out of all the raingauges across the majority of the months. Percentages were calculated for each raingauge compared to the ground level raingauge over the entire study period (Table 3.1). The percentage differences show that the ground level records more rainfall than the above ground raingauges. The Snowdon raingauge records the closest rainfall volumes to the ground level raingauge with a percentage of 92.8%. The unshielded Texas raingauge records the next closest to the ground level raingauge with a percentage of 92.1%, while the shielded Texas raingauge records the least amount with a percentage of 88.7 % when compared to the ground level raingauge. Between the wet and dry seasons, the relationship between the raingauges changed. In the wet season the unshielded Texas raingauge records 92.6 % of the rainfall recorded by the ground level, but is recording the most rainfall out of the above ground raingauges, by only 0.1 % over the Snowdon. The shielded raingauge records the least with 88.4 %. In the dry season, the Texas raingauge drops by 1.9 % compared to the ground level raingauge, while the Snowdon and shielded Texas raingauges increase by 0.4 % and 1.0 % respectively. This is based on a monthly time step, and there may be varying periods where the relationship between these raingauges changes.

The three Texas raingauges in their different configurations will be further analysed at a finer time step, however this is not possible for the monthly Snowdon raingauge.

Table 3.1: Percentage differences between the above ground raingauges compared to the ground level raingauge for the entire observation period, dry season and wet season

Raingauge Type	Overall %	Wet Season %	Dry Season %
Ground level	100.0	100.0	100.0
Snowdon	92.8	92.5	92.9
Texas (NS)	92.1	92.6	90.7
Texas (S)	88.7	88.4	89.4

3.3.2 Analysis of the measurement of rainfall events

From the observation period, 176 rainfall events were identified based on the criteria described in the data analysis section of this paper. The difference between the shielded and unshielded raingauges for each event, were calculated. A negative value indicates the unshielded raingauge recorded more for the event, while a positive value indicates the shielded raingauge recorded more. A trend was evident across the 176 events that showed the unshielded Texas raingauge recorded on average 0.245 mm (one tip) more rainfall per event. The difference between the shielded and unshielded raingauge was determined to be statistically significant (Table 3.2). The differences were then grouped into classes and the frequencies of each class (Figure 3.4) were calculated as a percentage.

Table 3.2 The output from the pair t-test between the shielded and unshielded Texas high-intensity raingauges located at the Meteorological station in the Cathedral Peak research catchments

Statistic	Value
Observations	176
t Stat	-5.964
t Critical one-tail	1.654
P (T<=t) one-tail	6.6346×10^{-9}

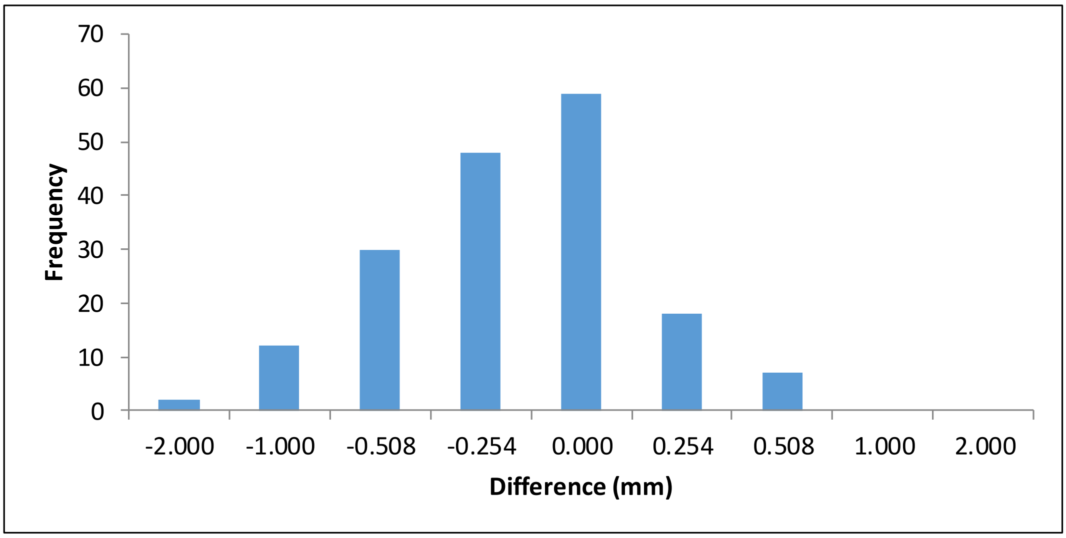


Figure 3.4: The frequency of occurrence of the differences recorded between the shielded and unshielded raingauge for the 176 rainfall events at the Meteorological station.

The unshielded raingauge recorded more rainfall in 52.27 % of events. For two of these events (1.14 %), the difference between the raingauges exceeded 2 mm, with the unshielded raingauge recording more rainfall. The shielded raingauge recorded more rainfall in only 14.20 % of the events. For these events, the difference between the raingauges never exceeded 1 mm. For 33.52 % of events there was no difference recorded between the shielded and unshielded raingauges.

In order to better understand the relationship identified above, possible influences based on the characteristics of events such as duration, rainfall depth, rainfall intensity and wind speed were analysed. The dataset was skewed as the representation of events at the higher rainfall volumes (>10 mm), was poor compared to the lower rainfall events. To reduce the skewness of the data set, the *log* of each characteristic was taken. This data was then used for the regression analysis. Depth and duration of the events was considered, and were found to have a statistical significance, however the error variance in the regressions was not constant, and therefore the regression was unreliable. As intensity is a product of duration and depth, a regression analysis considering intensity and wind speed, which is suggested in literature to act with intensity, was used. A full regression model fitting the effects of wind and intensity, as well as their interaction was run. The regression analysis showed that intensity had a significant negative (increased bias) effect (Figure 3.5) ($F_{1, 172} = 49.05$, $P < 0.001$), while wind speed reduced the bias (Figure 3.6) significantly ($F_{1,172} = 4.36$, $P = 0.038$) but their interaction was not significant ($F_{1,172} = 1.82$, $P = 0.179$). This is illustrated clearer in Figure 3.5 and 3.6, where the difference between the shielded and unshielded Texas high-intensity raingauges is plotted against the intensity recorded by the ground level raingauge, as well as the average wind speed recorded by the anemometer at the Meteorological station in Cathedral Peak.

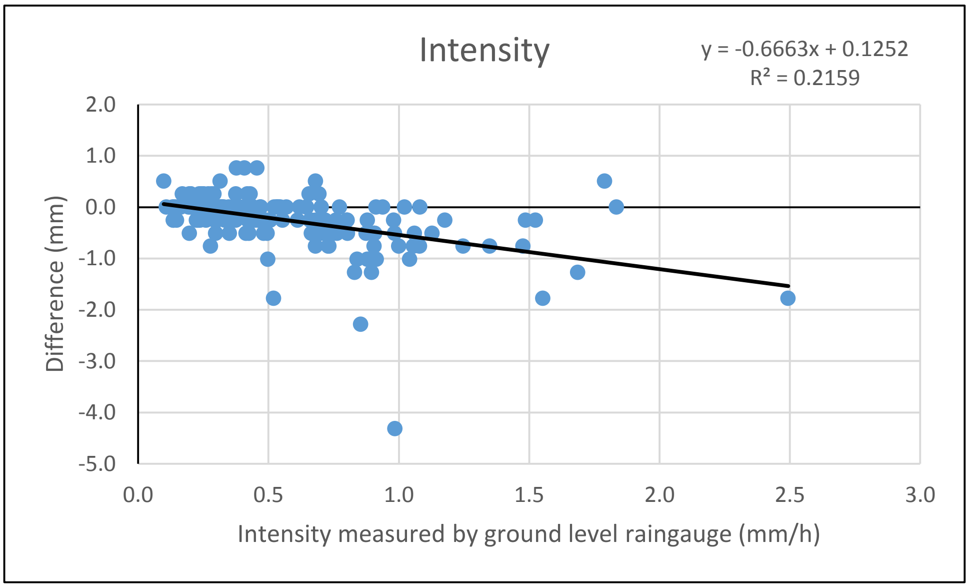


Figure 3.5: A regression analysis representing the relationship between raingauge type differences and the log of the average rainfall intensity of 176 events.

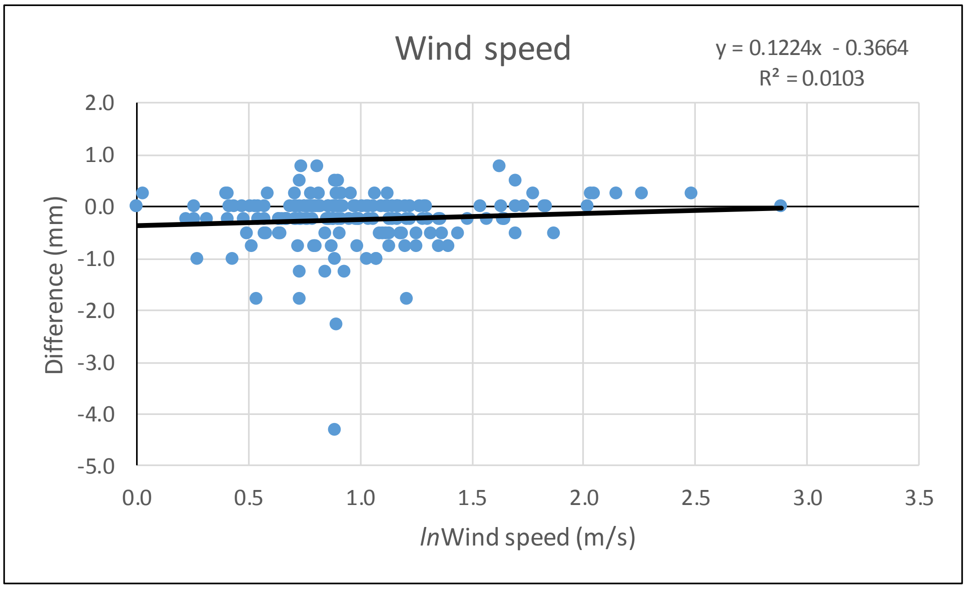


Figure 3.6: A regression analysis representing the relationship between raingauge type differences and the log of the average wind speed of 176 events.

It is evident from Figure 3.5 that with an increasing rainfall intensity, the difference between the raingauges increases. While with the increasing wind speed (Figure 3.6), there is a decrease in the difference between the raingauges. There is one extreme event which is an outlier in both Figure 3.5 and Figure 3.6, however it does not have a large influence on the difference between the raingauges as it is located in line with a large portion of other data points. Following this, a reduced regression model, which considers only the significant terms (in this case wind speed and intensity but not their interaction) was then run ($F_{2,173} = 26.58$, $P < 0.001$) and accounted for 22.6 % of the variance (Table 3.3).

Table 3.3: The estimates of parameters from the regression analysis of the log of wind speed and intensity using the reduced model

Parameter	estimate	CI95%	s.e	t-value	P-value
Constant	-0.0321	-0.2277 − -0.1635	0.0991	-0.32	0.746
*ln*Intensity	-0.6821	-0.8709 − -0.4932	0.0957	-7.13	<.001
*ln*Wind speed	0.1680	0.0088 – 0.3272	0.0806	2.08	0.039

The negative effect of intensity increases the difference by -0.68 mm for every 1 log scale unit of intensity, while the positive effect of wind speed reduced the difference by 0.17 mm for every 1 log scale unit. The regression analysis shows that the greatest difference between the raingauges is found during low wind speeds and high intensity rainfall.

3.4 Discussion

Following the 20 months of observation, several trends are evident. The ground level raingauge consistently records the most rainfall, at both the monthly time step as well as during the 176 rainfall events, which was expected, as it is the reference raingauge in the study. The Snowdon raingauge was the closest of the above ground raingauges. It recorded 7.2 % less rainfall than the ground level, but this is within range of what was expected from an above ground raingauge, based on studies found in literature (Essery and Wilcock, 1991; Duchon and Essenberg, 2001). The unshielded Texas raingauge was the closest to the Snowdon raingauge out of the two Texas raingauges. The Texas raingauge recorded 7.9% less rainfall than the ground level raingauge and only 0.7 % less than the Snowdon raingauge. The Snowdon raingauge recording more rainfall than the unshielded Texas raingauge was expected. What was not expected was the shielded Texas raingauge recording the least amount of rainfall. The shielded Texas records 11.3 % less rainfall than the ground level and 3.4 % less than the unshielded Texas.

The Snowdon raingauge recording the greater rainfall was expected. When comparing the Snowdon raingauge to the tipping-bucket raingauge, literature suggests that the Snowdon should record the greater rainfall due to the limitations of the tipping-bucket mechanism. The reason the Snowdon and manual raingauges in general are not as common now as in the past is due to the advantages the tipping-bucket raingauge provides with event based data and being automated. The small difference found between the Snowdon raingauge and the Texas tipping-bucket raingauge is of interest though. The repeated under recording by the tipping-bucket raingauge due to its mechanism has been found to be less evident at annual and possibly monthly time steps (Molini *et al.*, 2005; Shelton, 2009; Colli *et al.*, 2013). Therefore, the close relationship between the Snowdon and Texas instruments may be the result of the analysis at a monthly time step. Another factor may be that of the shield of the Snowdon raingauge. The shield may be having a negative effect on the Snowdon raingauge as is evident with the shielded Texas raingauge. The difference between the Snowdon raingauge and the unshielded Texas raingauge could be greater if the shield was not present. This however, is only speculation. The ground level raingauge is recording the closest value to the true rainfall possible, due to its reduced wind effects. Wind is the greatest influence on a raingauges ability to record rainfall, especially when the gauge is above ground (Michelson, 2004; Devine and Mekis, 2008). This explains why it would be expected that a shield would benefit the raingauge, however, this is not the finding at the Meteorological station in Cathedral Peak.

The wet season and dry seasons in Cathedral Peak experience different types of rainfall occurring from two different drivers. Based on the fact (Nanni, 1956) that the summer rainfall (wet season) is mostly from thunderstorms and the winter rainfall (dry season) is mostly as a result of frontal activity, the findings in Table 3.1 show an interesting pattern. This may not be very strong, but both shielded raingauges recorded closer to the ground level raingauge during the dry season than the unshielded raingauge. For the wet season, the unshielded raingauge actually recorded the closest rainfall to that of the reference ground level raingauge. Compared to the reference ground level raingauge, the unshielded Texas raingauge recorded 1.9 % more rainfall in the wet season relative to the dry season, while the Snowdon and shielded Texas raingauges recorded 0.4 % and 1.0 % more rainfall respectively. This could be due to the nature of the wet season rainfall which is high intensity. During high intensity events, shields have been found to be less effective. While for the dry season rainfall which is commonly light intensity, the shield is having an increased effect.

The underestimation of rainfall by the shield was not only occurring at the monthly time step, but also during 52.27 % of the 176 rainfall events. These events varied in duration, rainfall depth, intensity and wind speed. Duration and depth were determined to be of significance for the difference between the raingauges, but due to the inconsistent variance in the data set, the regression was unreliable. Intensity, which is rainfall volume over a period of time, is one of the characteristics which is highlighted in literature, along with wind speed, which has an influence on the performance of the shield. It was determined that intensity has a negative influence on the difference between the raingauges. Therefore, with a higher intensity, the unshielded raingauge recorded more rainfall by a larger volume then for the lower intensities. Wind speed was determined to have a positive influence, with the difference between the raingauges reducing with an increasing wind speed. Therefore, what has been found is that the difference between the raingauges is greatest for high intensity events with a low average wind speed and low for low intensity events with a high average wind speed. This can be linked into the finding above regarding the monthly time step, where the shield is more effective in the winter with the lighter intensity rainfall. Although this finding is true, wind speed and intensity are independent of each other when influencing the difference between the raingauges.

When initially analysing the individual events and characteristics, it was identified that the data set was skewed. This was caused by the lack of events with high rainfall volumes and wind speed and long duration. This is expected, as low volume rainfall events are more common than higher volume rainfall events. Over the observation period for this study, there were few higher volume rainfall events, as well as long duration events, which was a problem when identifying trends. The skewness of the data set was partially resolved by using the log scale. More data regarding the higher rainfall events will improve the confidence in trends identified at the higher rainfall volumes. To achieve this a longer observation period is needed, where the likelihood of recording a higher rainfall event is increased.

As both raingauges were Texas instruments, the only difference between them is the Nipher shield. It is understood that even with identical raingauges placed close to each other, they will record different rainfall volumes. This may partially account for the difference found at

Cathedral Peak, but the majority of the difference is most likely due to the Nipher shield. What this shows, is that the Nipher shield does aid the performance of the raingauge during high wind speeds. However, the shield is having a possible negative effect during the majority of events, as well as during the higher intensity events. Overall, the unshielded Texas raingauge records the closest rainfall volume to the ground level raingauge, performing better than the shielded Texas raingauge at the Cathedral Peak Meteorological station. It is also important to remember that in 33.52 % of the events, it was found that there was no difference between the raingauges. The average difference found between the raingauges was 0.245 mm, and when expressed as a percentage of the average rainfall volume from the events, equates to 3.2 %. When this is applied to the MAP of Cathedral Peak, 46.08 mm of rainfall is potentially not recorded by the shielded raingauge, which is a considerable amount. Cathedral Peak is also unique in its location and exposure to the elements, as it is a high altitude, mountainous meteorological station. This could partially explain, and should be considered, when comparing the difference in findings compared to the literature, in which studies were conducted at low lying, easily accessible, standard meteorological stations.

3.5 Conclusion

The Cathedral Peak Meteorological station provided the opportunity to conduct a comparison between the Snowdon raingauge, the Texas tipping-bucket raingauge and ground level raingauge. The site also provided the opportunity to determine the influence of shielding a tipping-bucket raingauge. After 20 months of observation, the comparison between the Snowdon raingauge and the Texas raingauge showed no statistically significant differences between the gauges at a monthly scale, while a significant difference was found between the shielded and unshielded Texas raingauges at the event scale. Intensity and wind speed showed to have statistical significance, but were independent of each other. The difference between the raingauges is greatest at low wind speed and high intensity.

The results indicate that shielding of the Texas raingauges does not improve the rainfall measurements. A better representation of the larger volume rainfall events is needed to draw confident conclusions about the shields influence during these events, and thus continued observation is recommended. A further recommendation is to have an additional unshielded Snowdon raingauge monitored alongside the shielded Snowdon to identify the shields effect on the historical raingauge, as well as to compare it to the ground level and other gauge configurations.

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CHAPTER 4: SYNTHESIS

There is a lack of research and data around rainfall processes and measurements in mountainous areas due the poor accessibility and remote nature of these areas, as well as the lack of high altitude raingauges and monitoring networks (Prudhomme, 1998; Barry, 2008). Thus, for monitoring networks that are located in high altitude mountainous areas, there is a need to have confidence in their accuracy. Mountainous long-term monitoring networks are important for the monitoring of global change (Toucher *et al.*, 2016). These are highly sensitive areas to the effects of global change (Rangwala and Miller, 2012; Kulkarni *et al.*, 2013). It is essential that the homogeneity of their data records is maintained, to allow for the identification of changes as a result of the right factors, and not due to changes in equipment (Bartokova *et al.*, 2014). This fact is gaining importance as modern equipment is replacing historical equipment found in many monitoring networks worldwide (Molini *et al.*, 2001; Strangeways, 2010; Tapiador *et al.*, 2012). New equipment has many advantages, such as better resolution measurements and possible improvements in accuracy, however this change can also affect the ability to correctly identify change (Bartokova *et al.*, 2014). As the upgrade and change of equipment has occurred at two important long-term monitoring sites in South Africa, the findings of this study are of important local interest. As Cathedral Peak and Jonkershoek are located in two very unique and important water generating areas of South Africa (Toucher *et al.*, 2016), the findings from studies conducted around the world could only be used as a guide as to the difference in precision of the historical raingauge network against the current raingauge network. Therefore, a local understanding of the influences of the mountainous areas and the changes in equipment on rainfall measurement in these two research catchments was needed. This could then be applied as a guide for other monitoring networks in similar locations.

The overall aim of this dissertation was to improve the understanding of the influences on rainfall measurements in mountainous areas. Beyond this, the research objectives were, (i) to conduct the cross-calibration at Cathedral Peak and Jonkershoek research catchments, (ii) to understand the influence of altitude, aspect and slope as well as raingauge design on rainfall measurement, (iii) to determine the influence of raingauge shielding and design in mountainous areas and whether rainfall event characteristics have an influence on these two factors. From this research, the final objective is to provide information and advice on the best practices in terms of raingauge design and setup for mountainous catchments in South Africa, with a focus on Cathedral Peak and Jonkershoek research catchments.

4.1 Cross-calibration of raingauges at two long-term monitoring sites

The cross-calibration between the historical and current raingauges in Cathedral Peak and Jonkershoek determined that there is no statistically significant difference between them. This indicates that there is no need to determine and apply correction factors to the historical and current rainfall records. Changes in the rainfall patterns due to global change can be identified by using the historical and current rainfall records without correction. Further to this, a partial trend showed that aspect and slope have a combined effect on the difference between the current and historical raingauges. This was possibly due to the tilted nature of the historical raingauges compared to the vertical position of the current raingauges. When facing the prevailing weather, the tilted historical raingauges recorded more rainfall at certain sites, compared to when they are facing away from the prevailing weather. This pattern was evident at sites IXA and XA where a downslope wind would occur and the raingauges are protected from the prevailing weather. These two sites showed the current raingauges recording up to 12 % more rainfall. This indicates that even though there is no significant difference between the raingauges, based on the location of the site, physical factors such as slope and aspect may influence the rainfall measurement more than raingauge design. In terms of raingauge design, it was found at Cathedral Peak, where both Texas and Davis raingauges were used, that the Davis raingauges tended to record more rainfall than the historical raingauges, while the Texas raingauges tended to record less. This may indicate that current raingauge design can also influence the difference between the current and historical raingauges, and needs to be considered when choosing a current raingauge to use.

4.2 Influences of shielding and raingauge design on rainfall measurement accuracy

Following 20 months of observation, the shielded Snowdon raingauge and unshielded Texas raingauge were determined to record within 8 % of the ground level raingauge at a monthly time step. Interestingly the shielded Texas raingauge recorded the least amount of rainfall, recording 12 % less than the ground level. This study again showed the close relationship between the historical and current raingauges at Cathedral Peak as was found in the cross-calibration. The influence of the shield on rainfall measurement was identified by removing the physical site factors and conducting the observation at the meteorological station. During the 176 events, which occurred during the observation period, the shielded raingauge recorded on average 0.245 mm (one tip) less rainfall per an event. This equates to 3% of rainfall at an annual scale. The difference between the shielded and unshielded Texas raingauges was determined to be significant. It was also found that the wind speed and intensity of an event had an influence on the difference between the raingauges. The difference was determined to be greatest when there was a higher rainfall intensity and lower wind speed. The intensity and wind speed were however independent of each other. The intensity increased the difference, while the wind speed reduced the difference between the raingauges.

4.3 Recommended best practices for mountainous catchments in South Africa

Monitoring of rainfall in the Cathedral Peak and Jonkershoek research catchments should continue with the current tipping-bucket raingauges. Throughout the study the Davis tipping-bucket raingauges were problematic and were often found blocked as they are not designed with sufficient prevention. The Texas high-intensity raingauges were more reliable and are built stronger for the long-term monitoring in high altitude mountainous catchments. As there is little difference between these two raingauges in terms of measurement ability, it is advised that any Davis tipping-bucket raingauges currently being used in the catchments be replaced by the Texas high-intensity raingauges. The findings of this study show that the raingauges in the catchments do not require shielding. The ground level raingauge provides the most accurate measure of rainfall, however it is not feasible, nor practical, to place throughout the research catchments. However, by continuing the monitoring of the ground level gauge at the meteorological station, it can be used as a benchmark gauge.

To ensure a good quality rainfall record from the various sites the catchments the following recommendations are made based on the experiences of this study,

- Calibration of the Texas high intensity raingauges should be undertaken at least once a year.
- The tipping-bucket raingauges are susceptible to blockages and should be checked and cleared on at least a monthly basis.

All though no data was lost as a result of a low battery, there was an issue during the winter months where the batteries would run flat faster than normal. Therefore, it is advised for mountainous catchments to use long lasting, good quality batteries which can withstand the high and low temperatures experienced in mountainous catchments.

4.4 Contributions of this research

This research project was part of the larger umbrella project: 'Establishment of a more robust observation network to improve understanding of global change in the sensitive and critical water supply area of the Drakensberg' focussed in the Cathedral Peak research catchments. This research projected addressed part of the third aim of the umbrella project: "to develop a hydrological monitoring plan which is compatible with the historical Cathedral Peak research catchments network and relevant for future climate change monitoring and transferable to other catchments" (Toucher *et al.,* 2016). This component of the umbrella project is important as the current monitoring in the Cathedral Peak research catchments needs to be compatible with the historical monitoring as it is necessary for the monitoring of global change and "identification of drivers of change" (Toucher *et al.*, 2016). This research has indicated that in both Cathedral Peak and Jonkershoek, using more modern raingauges in these catchments, should not affect the long-term monitoring of global change. This ensures that the historical records collected in these respective catchments can be used along with the current records to identify possible changes in these important and highly sensitive areas. As these cross-calibrations were conducted at the two sites mentioned, the results are site specific, and should not be directly applied to all sites. This study did however, provide insight into the relationship between historical Snowdon raingauges and the current Texas high intensity and Davis tipping-bucket raingauges, and rainfall measurement in two mountainous areas. This research also provided a test of shielding using an automated tipping-bucket raingauge, at a high-altitude site. The finding from the shield investigation at the Cathedral Peak meteorological station shows that the shield did not improve the performance of the raingauge. As a result, shielding was determined to not be necessary in the Cathedral Peak research catchments. The unshielded Texas raingauges showed that it provides an adequate measure of rainfall, even when compared to the shielded Snowdon and ground level raingauges.

4.5 Conclusion

This research project has addressed its main aim of improving the understanding of the influences on rainfall measurement in mountainous areas. Historical manual raingauges and the more modern tipping-bucket raingauges show no significant difference when used in a high altitude mountainous monitoring network. At a monthly scale, the difference between the shielded Snowdon raingauge and the Texas unshielded raingauge, was not statistically significant, while at the event scale the difference between the shielded and unshielded Texas raingauge was statistically significant. A key finding was that of a partial trend where a raingauge positioned at the same angle as the slope following the hydrological method for measuring rainfall, would tend to record more rainfall on a slope facing the prevailing weather, over a vertical raingauge following the meteorological method for recording rainfall. The reverse of this would occur on the more sheltered slopes facing away from the prevailing weather, receiving a downslope wind. This effect is possibly due to the tilt and difference in raingauge design, and shielding of the current raingauges would not be an effective solution. This was determined by the investigation into the shielding of current raingauges, which showed that the shield has a negative effect on the rainfall measurement of a Texas high intensity raingauge, with the greatest under recording occurring during high intensity low wind speed rainfall events. Thus, suggesting that shielding of current raingauges is not required in these mountainous monitoring networks.

4.6 Recommendations

As this was a master’s research project, time was limited. A longer observation period, especially since this is a rainfall based study, which is a highly variable component, is recommended. This would allow for the possible trends identified here, to become clearer and more evident. Seasonality could then also be assessed with more confidence. The most important part with a longer observation period would be better representation of the higher rainfall events. This would allow for a better understanding of the shields influence during such events.

With the uses of both the Texas high intensity and Davis tipping-bucket raingauges at the Cathedral Peak site and the finding that at the sites where the current raingauges recorded more rainfall had Davis raingauges, there is a need to test Texas versus the Davis raingauges.

This should be conducted at the meteorological station, and should consist of two or more Davis and Texas raingauges observed over a sufficient period while placed within close proximity. Having more than one of each raingauge type would provide a better representation of each design and would not be effected by a faulty gauge. By conducting this at the meteorological station, it also removes physical site characteristics, such as slope and aspect, which may have been a factor in the cross-calibration.

The finding that slope and aspect influence the difference between the current and historical raingauges together could be further tested by having a better representation of raingauges on sheltered slopes, protected from the prevailing weather. These slopes only had two raingauges on them for the cross-calibration. With several more raingauge sites allocated to these slopes, it could provide a clearer and more confident trend. This could allow for a clearer indication that downslope winds cause an under recording by hydrological raingauges, while facing the prevailing weather causes an under-recording by the vertical raingauges.

The final recommendation is, to install and observe an unshielded Snowdon raingauge alongside the unshielded Texas and ground level raingauges. This would further the knowledge regarding the shield, as the close nature between the unshielded Texas and the shielded Snowdon could be due to the shield and had the shield not been present, the difference between the Snowdon and Texas may be larger, or worse. Another view of this would be to then also have a period where the shield is removed from the Texas raingauge that was shielded, and continue to monitor it and the other Texas with the ground level for another 20 months, to ensure that the raingauge was not the cause of the difference identified as the shield. Added to this, the raingauge shield used on the current Texas raingauge, was a shield used historically in the Cathedral Peak catchments, and is based on the Nipher design. A ring was modified to allow for the Texas raingauge to fit into the shield. This shield is not a modern design, and may therefore be ineffective with a more modern raingauge. Thus, the possible design and construction of a ‘new age’ shield to be used specifically with a Texas high intensity raingauge may show a different finding at this site, possibly improving the raingauges ability to record rainfall. Therefore, testing the Snowdon without a shield may allow for a better understanding of the shield and its use with more modern raingauges.

4.7 References

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5. APPENDIX

Table A1 The percentage difference between the rainfall measured by the historical and the current raingauge in terms of the current raingauge, for every month of the study at Cathedral Peak. The greyed out blocks indicate periods where the values were removed due to errors.

	Met	IIB	IIC	IIIB	IVB	VA	VIIA	VIIC	VIIIA	IXA	XA
Feb 14	▨	▨	▨	▨	▨	▨	▨	▨	-1.78	-1.03	8.59
Mar 14	1.96	-14.04	-12.66	-5.07	1.20	-1.55	-14.80	31.04	-12.53	-9.77	0.76
Apr 14	7.13	2.61	-4.79	3.68	0.91	-4.96	-13.02	1.57	▨	4.37	20.48
May 14	▨	▨	1.70	▨	▨	▨	▨	▨	▨	▨	▨
Jun 14	▨	▨	-10.97	▨	▨	▨	▨	▨	▨	▨	▨
Dec 14	-12.98	▨	-9.25	-7.62	▨	▨	▨	1.01	▨	▨	7.64
Jan 15	1.23	▨	3.04	-12.84	-6.58	-12.96	▨	-3.43	▨	▨	8.55
Feb 15	5.21	▨	9.47	-18.40	-7.60	-3.83	16.11	-37.51	1.48	▨	0.59
Mar 15	0.24	9.86	17.70	-11.99	▨	-6.99	7.23	-0.52	4.55	16.88	-4.41
Apr 15	11.09	3.13	7.41	4.42	▨	-19.30	-11.35	-1.16	24.24	37.00	12.55
May 15	▨	17.70	8.63	25.93	▨	▨	▨	▨	▨	▨	32.66
Jun 15	▨	▨	▨	43.02	▨	2.79	▨	▨	▨	▨	▨
Jul 15	1.66	10.92	▨	-0.45	-12.31	-25.33	-4.52	6.95	17.27	25.74	22.15
Aug 15	4.24	▨	▨	▨	-2.35	▨	-12.17	-7.08	19.97	23.22	9.30
Sep 15	-10.28	27.26	3.22	1.53	-39.98	-30.36	-23.08	-22.87	22.67	11.35	2.66
Oct 15	1.66	5.72	13.85	-0.68	▨	-18.23	▨	0.03	15.03	7.82	0.30
Nov 15	0.29	3.23	11.92	-3.26	▨	-18.47	2.11	10.85	8.09	14.40	13.17
Dec 15	-4.07	-1.10	-1.21	-1.72	▨	-21.97	-15.95	-8.17	3.32	18.26	2.79
Jan 16	-0.72	▨	1.29	-11.60	▨	-6.03	4.32	-17.04	-2.76	11.30	5.13
Feb 16	-4.50	▨	4.81	-4.49	-16.95	-5.21	9.43	▨	-1.90	19.04	4.68
Mar 16	-0.22	0.76	11.67	▨	▨	-3.04	0.38	▨	5.05	18.12	7.16
Apr 16	0.97	-30.51	9.02	1.10	▨	-26.99	▨	-31.74	3.24	18.05	8.90
May 16	-4.15	13.68	15.76	1.97	-22.78	-18.25	-7.47	-18.38	5.13	13.35	13.00
Jun 16	19.34	▨	▨	5.89	-38.95	▨	-2.51	2.79	14.53	30.56	25.93
July 16	-5.72	-15.64	-0.78	-18.26	-19.74	▨	-4.08	-2.10	-34.53	-9.68	3.24
Aug 16	-0.30	0.49	24.18	-5.43	-33.60	-5.26	14.00	▨	3.00	17.22	22.00
Sep 16	-13.64	16.25	9.06	1.58	-49.86	-53.16	-73.36	19.45	3.42	8.08	6.15

Table A2 The percentage difference between the rainfall measured by the current and historical raingauge in terms of the current raingauge, for every month of the study at Jonkershoek. The greyed out blocks indicate periods where data was removed due to errors.

	7B	9B	11B	12B	13B	15B	19B	20B
Jul 11	2.29	-2.85	-9.12	9.12	8.55	-2.32	7.78	-6.02
Aug 11	2.77	-4.97	-2.35	0.35	-7.86	-2.23	0.91	-0.71
Sep 11	-0.41	-18.38	-12.81	0.67	-8.61	5.85	-0.74	-32.79
Oct 11	-0.98	-4.44	-6.72	5.26	-19.01	21.18	-13.99	-11.39
Nov 11	2.45	-5.90	4.72	0.93	-14.12		6.06	-6.77
Dec 11	4.84	-12.03	9.72	6.39	-16.74	8.75	20.50	-7.17
Jan 12	10.54	-16.13	15.20	16.10	-10.65	12.76	22.00	-0.91
Feb 12	1.28	-26.25	20.00	16.39	-26.14	29.81	19.23	-22.62
Mar 12	3.28	-20.46	-10.74	-6.55	-30.49	1.95	-0.74	-19.60
Apr 12	10.00	-5.97	-5.69	-13.39	-25.24	6.34	6.38	-28.97