ESTABLISHMENT OF AND DEMONSTRATION OF THE POTENTIAL OF THE CATHEDRAL PEAK RESEARCH CATCHMENTS AS A LIVING LABORATORY

Report to the

WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

BACKGROUND AND RATIONALE

High altitude catchments are often important headwater catchments. However, much uncertainty surrounds environmental change and its impacts on hydrological responses, particularly in these high altitude catchments. It is, therefore, imperative to improve our understanding of water distribution and movement in these catchments as any changes in the hydrological responses from these catchments could have significant social, economic and environmental consequences downstream. To be able to achieve this understanding, detect changes and reduce uncertainty, long-term hydrological monitoring is crucial. Long-term hydrological monitoring sites, however, are limited particularly in high altitude regions. Thus, any long-term hydrological monitoring initiative should be supported and the best use of the data be made. This Water Research Commission (WRC) project built on the South African Environmental Observation Node's (SAEON) initiative to resurrect streamflow and climatic monitoring in the Cathedral Peak research catchments. The long history, the wealth of data collected, and knowledge that exists surrounding the Cathedral Peak research catchments makes them an ideal site for long-term monitoring to understand environmental change, as well as providing an opportunity for capacity building.

PROJECT OBJECTIVES

The overall objective of the project was to improve the understanding of environmental change by collecting and analyzing current and historical data from the Cathedral Peak catchments, and through this refining the design for a robust and relevant monitoring network for environmental change monitoring while at the same time building capacity.

The aims of this project were:

1. To compile a database of relevant historic data collected over the past 50 years from the Cathedral Peak research catchments.
2. To infill and extend the historical rainfall and streamflow record of the Cathedral Peak research catchments to the present.
3. 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.
4. To determine whether any changes in hydrological response are already evident, and to understand the underlying causes.
5. To improve the understanding of rainfall distribution across the escarpment.
6. To develop the Cathedral Peak research catchments into a living laboratory for undergraduate and postgraduate student training as well as for technical skills transfer and knowledge building.

STRUCTURE OF THE REPORT

Chapter 1:	Background to the project.
Chapter 2:	Description of the Cathedral Peak research catchments and review the hydrological history of the catchments.
Chapter 3:	Cataloguing of the historical data from the Cathedral Peak research catchments, as well as error checking, data protocols and management.
Chapter 4:	Proposed hydrological monitoring plan developed for the Cathedral Peak research catchments.
Chapter 5:	Change detection study undertaken on the temperature, rainfall and streamflow records from the catchments for both the historical and current period of data.
Chapter 6:	Improving the spatial understanding of the rainfall distribution across the catchments.
Chapter 7:	Details the capacity building activities throughout the project, and the activities related to this.
Chapter 8:	General discussion and recommendations for the way forward.

CATCHMENT DESCRIPTION AND HISTORY

Controversy around the possible negative impacts of large-scale afforestation with exotic trees on the water resources and landscape of South Africa led to the establishment of the Cathedral Peak Forestry Influences Research Station in 1938, with monitoring being initiated in October 1948. Over the years, the Cathedral Peak catchments have been used to examine the impacts of various land management and treatment practices on hydrological responses. The Cathedral Peak research catchments (29° 00' S; 29° 15' E) are located in the northern part of the uKhahlamba Drakensberg, ranging in altitude from 1 820 m.a.s.l to 2 463 m.a.s.l. The catchments fall within the summer rainfall region, with a mean annual precipitation (MAP) of approximately 1 400 mm. The initial treatment plan for the ten catchments established at that time was that besides Catchment I, which was to be used to assess the impacts of grazing, and Catchment IX, which was a burn exclusion catchment, the remaining catchments were to be planted to commercial forestry over a period of time. Over the course of the research programme the treatments were not all implemented and during March 1972 the research programme was modified. At this time a further five catchments were established to allow for the impacts of various burning treatments on grassland and scrub vegetation to be assessed. Monitoring in the Cathedral Peak research catchments continued until 1995 when, due to lack of funding, monitoring in the catchments ceased. Ezemvelo KZN Wildlife (EKZNW) continued to fund the the burning treatments until 2000 when budget constraints resulted in the catchments being managed as part of the burning programme for Cathedral Peak.

Data gathered from the monitoring of the Cathedral Peak research catchments under various treatments has contributed significantly to hydrological understanding. Research by Nänni showed the decreases in runoff in the afforested catchments relative to the grassland catchment. This work and later analyses of the data from the Cathedral Peak catchments have underpinned the legislation to control afforestation and the estimation of water use of commercial afforestation to date. The second area to which research undertaken using the data from the Cathedral Peak research catchments has contributed significantly is hydrological model development and related research. Using the Cathedral Peak catchments and data measurements from these catchments, a model for estimating catchment evapotranspiration was developed by Schulze (1975) and this formed the building blocks for the physically-based, daily time-step *ACRU* agrohydrological model which was later developed. Further testing and development of the ACRU model has been undertaken over time using data from the catchments. The prescribed burning treatments and the accidental wildfires that pass through the Cathedral Peak research catchments have also allowed the impacts of fire on the hydrological responses of the catchments to be investigated. Results from these studies showed that fire had no significant impact on total streamflows of the grassland catchments, and only a minor change in stormflows.

Although substantial use of the data from the Cathedral Peak catchments has been made to improve hydrological understanding, there is still much that can be done. The long term climatic and streamflow records that exist for Cathedral Peak prior to the 1990s, offer the opportunity for changes in climate and hydrological responses to be detected, monitored and analysed to allow for improved process understanding. Thus, in 2011 the SAEON Grasslands-Forests-Wetlands Node began the process of restoring monitoring in the catchments.

DATA COLLECTION AND MANAGEMENT

Historical data

A wealth of data has been collected for the Cathedral Peak research catchments, with the Council for Scientific and Industrial Research (CSIR) being the custodian of the hydrological and climatological datasets until SAEONs involvement in the catchments. Historically there were two primary weather stations recording climatic variables for the research catchments, namely a station located at the top of Mike's Pass (1948-1995) and a climate station located near the research office (1952-1993). In addition to these meteorological stations, precipitation was historically monitored at twenty-five sites across catchments I-X and at a further nineteen sites across Catchments XI-XV. Evaporation was measured at the Mike's Pass meteorological station until 1984 using an A-pan, after which the automated weather station was installed. In addition, a Lysimeter was installed in Catchment VI, however, there were problems with wind-drift during the time it was operational. From September 1990 to June 1995 evaporation was continuously monitored in Catchment IV using the Bowen Ratio energy balance technique.

Streamflow monitoring was initiated in Catchments I-IX during the late 1940s and 1950s, Catchment X during the 1960s and in the 1970s in Catchments XI-XV. Groundwater was monitored for the 1994/1995 hydrological year for two boreholes drilled in Catchment VI. When cleaning the weirs, qualitative observations on the volume of silt removed from the weirs were made for selected catchments. Water chemistry sampling was initiated in Cathedral Peak in 1981, samples were analysed for Na^+, K^+, Ca^+, Mg^+, Cl^-, SO_4^{2-}, HCO_3, NH_4^+, PO_4^{3-}, NO_3^-, TP (Total Phosphorus), KN, Si and F. The pH and conductivity levels were assessed on site.

Quality Control of the Historical Data
To error check the rainfall records, a graphical analysis of the historical data records was undertaken which showed that a number of monthly records were missing. Following this, the historical rainfall records were error checked by comparing neighbouring and similar gauges to flag any outliers. Given the missing records and the flagged errors, the historical rainfall records needed to be infilled. Five rainfall infilling techniques, *viz.* Nearest Neighbour by Distance, Nearest Neighbour by Correlation, Inverse Distance Weighted, average of gauges selected by correlation and Weighted Average of gauges selected by correlation methods, were investigated to determine the best suited technique to use to infill the Cathedral Peak historical rainfall records. A statistical comparison between the methods indicated that for most gauges, the Nearest Neighbour by Correlation method gave the best results thus it was used to infill the rainfall records.

Error checking and extension of streamflow records focused on catchments III, IV, VI, VII and IX. The daily data was graphed to check for outliers and anomalies. Besides missing records, no outliers or anomalies were found. Using the physical-conceptual ACRU agrohydrological model and the rainfall records from nearby stations, the streamflow records were extended.

With any long-term monitoring site it is essential that the data collected is of high quality. Thus, with the reestablishment of monitoring in the catchments the quality of the data must be ensured by following a set of data collection procedures and protocols on each site visit. These standard procedures and protocols maintain raw data quality, govern the data processing and error checking procedures, thus providing stationarity to time series data. These procedures and protocols, including the protection of equipment and personal safety are detailed in the report. On return from the field, it is therefore imperative that the data be copied immediately from the field laptop (or storage device such as a shuttle) to a network drive (that is backed up regularly) using a logical directory and file structure. Before the data is uploaded onto the SAEON data portal it is necessary to verify the data integrity downloaded in the field. Visual inspection of the data in a graph as well as confirmation of the continuity of the data since the last download is necessary. Any available meta data should be linked to the data records.

Both the historical and current data from the Cathedral Peak research catchments, together with the meta data, will be stored and made available through the SAEON data portal. The SAEON data portal houses a diversity of data types, each supported by a background system. The Observations database was specifically developed for the purpose of housing historical and current observations of streamflow and climatic data. When uploading data to the repository there are strict requirements on the metadata required which adhere to international standards.

Cross-calibration of raingauges
With the re-establishment of the Cathedral Peak research catchments, modern Davis tipping bucket and Texas High intensity raingauges were installed to replace the historical Snowdon raingauges. The modern and historical raingauges have several differences that result in varying measurements of rainfall at a location. Thus to ensure the compatibility of the historical and current rainfall records in the Cathedral Peak research catchments, a cross-calibration of the modern and the historical raingauges was conducted. In addition, the question of the accuracy of the Snowden and modern

raingauge was addressed through comparison against a ground level gauge, which the WMO considers to be most accurate. The influence of the Nipher shield was also investigated.

Across the Cathedral Peak sites, the historical and modern raingauges were found to record similar rainfall volumes for the 16 months monitored, with the difference never exceeding 9%. Whether the historical raingauge records more rainfall or the modern raingauge does, varies from site to site, and from month to month. There is no consistent pattern evident. At slopes greater than 20%, modern raingauges appear to record more rainfall. This may be attributable to the tilt of historical gauges while the modern gauges are upright. In order to identify whether the historical or modern raingauges are more accurate, the ground level raingauge was used as a reference gauge. The ground level gauge consistently recorded the highest rainfall totals. Based on overall totals, the historical raingauge is less accurate than the modern gauge at the Mike's Pass meteorological site as its total rainfall is less. However, if only months with more than 3 mm of rainfall are considered, then the difference between the historical and modern raingauge is only 0.6% which is insignificant given the errors associated with rainfall measurement.

PROPOSED HYDROLOGICAL MONITORING PLAN

The need for quality, long-term datasets has become more important with the current impacts of anthropogenic activities on the environment. These long-term datasets can only be obtained through establishing suitable, sustainable hydrological monitoring networks that adequately characterize the properties, distribution, and circulation of water in the atmosphere (vapour fluxes, precipitation), on the land (soil moisture, overland flow, groundwater), and in surface waters (rivers, reservoirs, wetland storage). The Cathedral Peak research catchments are ideal as a long-term monitoring site for global change as they are high altitude catchments, have catchments both in pristine and damaged condition (previously afforested catchments), and have a long historical record (although interrupted). The hydrological monitoring network designed for the catchments needs to be comparable with the historical network to benefit from the historic data for change detection and identification of drivers of change as well as being relevant for monitoring changes and thresholds or tipping points in system behaviour into the future. Meeting this requirement requires foresight to combine improvements and new approaches to observation and monitoring while maintaining compatibility with historic data. The datasets need to be available and compatible to further develop hydrological models that have a greater consistency with the real world, incorporating improved process understanding. In addition, the proposed monitoring needs to fulfil the requirements that researchers will have in the future when addressing environmental change. Thus, the monitoring plan for the Cathedral Peak catchments proposed here is to have catchment-wide climatological monitoring, streamflow monitoring in key catchments and then focused, detailed monitoring in Catchment VI with the full array of evaporation, soil moisture and groundwater monitoring.

The full automatic weather station at the Mike's Pass meteorological station and at the research office has been re-established, and to supplement this the historical array of raingauges in the catchment have been reinstated. Given the aim of ensuring the sustainability of the monitoring network and the costs associated with weir maintenance it was recognised that streamflow monitoring needed to be rationalised, thus the flows at the outlets of Catchments III, IV, V, VI, VII and XI should be monitored. To allow for studies to improve process understanding and the influences of change, it is necessary to be able to close the hydrological cycle thus monitoring of evaporation, soil moisture and groundwater is needed in Catchment VI. Beyond this, to address more complex questions, carbon flux measurements, water quality monitoring and various other focussed studies may be required.

DETECTION OF CHANGES IN THE CATHEDRAL PEAK REGION

To achieve the objective of determining whether trends in rainfall, temperature and streamflow are evident in the Cathedral Peak area, the approach followed comprised of four main stages, namely data quality control, exploratory or visual analysis, application of statistical tests and lastly the interpretation of trends. Quality control is an essential component of the first and second stage which includes obtaining and preparing the data in order to compile a suitable dataset for analysis. The detection study made use of the error checked and infilled rainfall records from this project, and the extended streamflow records. Data for a historical period and a current period was analysed for each variable. The Mann-Kendall non-parametric statistical test was used to detect the significance of trends in the historical records, while the Mann-Whitney test was used to determine differences between the historical and current records.

Consistent positive trends in minimum, maximum and mean temperature across the three stations analysed indicated warming through the historic period. Due to temperature records for only Mike's Pass meteorological station being available for the current period, it was not possible to conclusively determine if changes were evident between the historical and current periods. Trends in the historical rainfall records at a daily and monthly level indicated a drying through the historical record, particularly in autumn. A comparison of the historical rainfall period to the rainfall available for the current period showed an increase in the number of raindays in summer and winter, an increase in the number of events greater than 20 mm in summer and autumn and an increase in the 2-day maximum rainfall. These results begin to indicate changes in the rainfall patterns and extremes, however, they do not give an indication of whether there is a general wetting or drying trend between the historical and current period.

Decreasing trends are evident in the historical streamflow which correspond to the drying trends shown in the historical rainfall. During the historical period analysed the land use in the catchments assessed remained constant, thus it is reasoned that the intensification of the trends in rainfall through the hydrological cycle are the cause behind the negative trends being evident in streamflow across all time steps and seasons while a few statistically significant negative trends are evident in rainfall. Catchments IV, V and VI where monitoring has resumed have remained as grassland, Catchment VII was planted to commercial forestry for a short period but has been rehabilitated to grassland. Monitoring in Catchments III and IX, where it would be possible to determine the influence of land use change in comparison to climate change, has not yet resumed. Given this, and the short records for the current period it was not possible to undertake an attribution study at this stage.

IMPROVING THE UNDERSTANDING OF RAINFALL DISTRIBUTION ACROSS THE CATHEDRAL PEAK CATCHMENTS

With a longer data record now available, recent advancements in interpolation methods and the increasing pressure on water resources it was necessary to revise the rainfall estimation for the Cathedral Peak research catchments. The objective of this research was to ascertain if the use of contemporary geo-statistical interpolation methods provided any improved estimates and understanding of the rainfall distribution across the Cathedral Peak catchments in the Drakensberg escarpment region. The historical monthly rainfall data error checked and infilled through this project was used.

Analysis of the mean annual, wet and dry season rainfall confirmed a strong wet and dry season trend. On average, 83% of the annual rainfall occurs during the wet season (September to February) with the North facing gauges receiving the most rainfall during both wet and dry seasons. Regression analysis was used to determine if the considered predictor variables (altitude, aspect, latitude and longitude) showed any significance in explaining the variation in the annual, wet and dry season rainfall. With fitted parameters of the regression model and of the residual variogram, regression kriging was used to derive rainfall predictions at all locations.

The Regression kriging method showed to be a useful tool in characterizing the rainfall distribution for the Cathedral Peak catchments. Predictions indicated that the overall rainfall distribution for the area is strongly directional particularly for the long term mean annual rainfall and for the wet season, as well as a significant effect on rainfall distribution due to altitude. Longitude and altitude were shown to have lower significances in explaining the dry season rainfall variability which may be due to the different effect of topography on frontal systems compared to the effect on convective rainfall. However, the use of long term means to characterize rainfall for an area which receives predominantly sub daily short duration events is not fully representative of the nature of rainfall in the area and can also explain the high root mean square errors (RMSE). Thus, a temporal and spatial analysis of rain event properties for the area was undertaken.

Daily rainfall data was collected from 23 rainfall stations in the Cathedral Peak area for a concurrent recording period, spanning one year from 2 December 2013 to 2 December 2014. For each rainfall station mean event rain rates, rain event depth, rain event duration as well as daily rainfall totals and the number of rain days were calculated. Quantile regression (QR) was then used to examine the relationship between all parts of the rainfall distribution for different rain event depths with different predictor variables (altitude, longitude, aspect and slope). The spline interpolation technique was used to produce surface maps of both daily and sub-daily rainfall properties for the Cathedral Peak catchments.

Analysis of daily rainfall characteristics at an annual time interval as well as the wet season and dry season showed a general decrease in the total daily rainfall and total number of rain days from west to east. In terms of altitude, lower altitude raingauges received higher total daily rainfall in a higher total number of raindays compared to high altitude raingauges. On a seasonal basis, analysis of daily rainfall properties showed that for the annual and wet season, low altitude raingauges received higher total daily rainfalls in fewer raindays compared to the dry season. With respect to both altitude and aspect, raingauges positioned at similar altitudes received diverse rainfall amounts over varying number of raindays due to differing aspects. QR proved to be a useful method in providing more insightful information on the rainfall-predictor relationship in Cathedral Peak, as it analysed the complete conditional distribution of rain event depths for the area as opposed to just the mean state.

DEVELOPMENT OF THE CATHEDRAL PEAK CATCHMENTS AS A LIVING LABORATORY

Besides the substantial value of the data collected in the Cathedral Peak catchments and the vast opportunities for improving hydrological understanding, the catchments have immense value as a living laboratory where training and the development of skills can take place. Postgraduate studies are becoming increasingly important for skills development, training and exposure to research due to the rapidly growing undergraduate class sizes. The large undergraduate class together with the limited facilities and resources result in undergraduate students sharing equipment, having limited hands-on and practical experience. Thus, during the postgraduate years it is essential that students undertake hands-on practical training, have greater exposure to scientific method and rigor as well as exposure to research. The use of living laboratories such as the Cathedral Peak research catchments allows this exposure. Using living laboratories allows students to learn through experience and visualisation, allows for practical hands-on training and the inclusion of students in ongoing “umbrella” research projects. A further benefit of using living laboratories such as the Cathedral Peak catchments for postgraduate training is that they allow for the pooling of resources, expertise, capital and physical resources. Over the course of this project, the Cathedral Peak research catchments and the data from them have been used in several aspects of the Hydrology Honours program and Masters of Science degrees at the University of KwaZulu-Natal (UKZN).

Skills and technical knowledge related to hydrological field instrumentation is in dire shortage currently in South Africa, with many of those considered experts nearing retirement age. Technical skills transfer has been a strong component of this project. This has occurred at multiple levels with technicians from UKZN working alongside newly appointed technicians at SAEON, teaching them on the job, in field and in the laboratory about various approaches, deploying, calibrating and maintaining instrument networks. Academics on the program have provided advisory support to the SAEON program on a continual basis.

Overall, the project has been successful in terms of its objectives to advance the initiative of SAEON to re-establish monitoring in the Cathedral Peak catchments, and to show the potential of the catchments for use as a living laboratory for training and capacity building. However, through the course of the project barriers have been identified that may hinder the further development and use of the catchments as a living laboratory. The successes identified include:

- The securing of funding for the basic and more specialised monitoring equipment.
- The strong collaboration between UKZN and SAEON which has provided a model for how government investment in research infrastructure, combined with academic collaboration and student support from WRC funding, can operate in unison to achieve the intended value of the platform while at the same time addressing critical knowledge and training requirements.

- The gathering of knowledge from scientists who worked in the catchments previously, solidifying the base of knowledge from which advancements can be made moving forward.

Thehe barriers identified include:

- Concerns around security in the research catchments.
- Resource constraints in terms of human capital and student funding.
- The development and population of a data management systems.

ACHIEVEMENT OF OBJECTIVES

The project objectives have been fully achieved with the exception of Aim 4. The relevant chapters that address each of the aims are given in the following table.

AIM	Chapter
1. To compile a database of relevant historic data collected over the past 50 years from the Cathedral Peak research catchments.	Chapter 2 and 3, attached DVD
2. To infill and extend the historical rainfall and streamflow record of the Cathedral Peak research catchments to the present.	Chapter 3; attached DVD
3. 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.	Chapter 4
4. To determine whether any changes in hydrological response are already evident, and to understand the underlying causes.	Chapter 5
5. To improve the understanding of rainfall distribution across the escarpment.	Chapter 6
6. To develop the Cathedral Peak research catchments into a living laboratory for undergraduate and postgraduate student training as well as for technical skills transfer and knowledge building.	Chapter 7

Aim 4 was not fully addressed in that the results of the detection study were inconclusive due to the short length of the current records, thus the attribution study alluded to in the aim could not be undertaken.

RECOMMENDATIONS

The recommendations from this project are:

- The SAEON initiative to further the development of the Cathedral Peak long term observation platform should be supported and encouraged.
- Strong collaboration and partnerships that make use of the platform to further hydrological understanding should be explored.
- Mechanisms to support the development and management of the Cathedral Peak long term observation platform should be explored, as should mechanisms to develop collaborations and partnerships.

- Mechanisms to secure postgraduate student funding to support student activities on the platform need to be investigated.
- Use of the Cathedral Peak catchments as a living laboratory for postgraduate field schools should continue, with the development of inter-disciplinary global change field schools being pursued.
- The continued emphasis on technical skills development and transfer using the catchments to gain hands-on experience and learning opportunities should be an ongoing priority.
- Future studies should focus on change detection as the record extends, and attribution studies to determine the cause of the change. Detailed process level research, with intentional efforts to span across disciplines. With these leading to the improvement of existing and new models both in the description of processes and parametrisation of the models.

TECHNOLOGY TRANSFER AND CAPACITY BUILDING

Individuals who benefited from the project and contributed to it in their postgraduate degrees included 4 MSc students and 3 BSc Honours student. Their postgraduate research overlapped with this project to varying extents. Four of these students had completed their degrees at the time of writing this report. Additionally, 4 interns contributed to the project and gained knowledge and skills. An Honours field school which was attended by five Honours students from University of Zululand, University of Venda and UKZN was held through this project. The technical skills capacity of SAEON was enhanced through this project, with the technicians from UKZN working alongside newly appointed technicians at SAEON, and a technical training workshop. Academics on the program have provided advisory support to the SAEON program on a continual basis.

Technology transfer was facilitated in the project through publishing of research results (3 peer-reviewed journal papers) and giving presentations at conferences (9 presentations).

Further details on capacity building and technology transfer are available in the report.

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1. BACKGROUND AND INTRODUCTION

South Africa is a water scarce country in which the availability of "water of an acceptable quality" is considered a potentially significant development constraint (Scholes, 2001). However, much uncertainty surrounds environmental change and its impacts on hydrological responses, particularly in high altitude catchments. High altitude catchments are often important headwater catchments. It is, therefore, imperative to improve our understanding of water distribution and movement in these catchments as any changes in the hydrological responses from these catchments could have significant social, economic and environmental consequences downstream. This improved understanding and the information generated from it is sought after to provide policy and government agencies with appropriate information to direct planning and policy formulation (Stuart-Hill and Schulze, 2010). To be able to achieve this understanding, detect changes and reduce uncertainty, long-term hydrological monitoring is an essential and important foundation.

Long-term hydrological monitoring sites, however, are limited particularly in high altitude regions. Thus, any long-term hydrological monitoring initiative should be supported and the best use of the data be made. This Water Research Commission (WRC) project built on the South African Environmental Observation Node's (SAEON) initiative to resurrect streamflow and climatic monitoring in the Cathedral Peak research catchments and the ACCESS Theme 3 (Water) programme. The long history, the wealth of data collected, and knowledge that exists surrounding the Cathedral Peak research catchments makes them an ideal site for long-term monitoring to understand environmental change, as well as providing an opportunity for capacity building. SAEON, together with funding from the DST, NRF, ACCESS, DEA and working in collaboration with Ezemvelo KZN Wildlife (EKZNW), reestablished monitoring in the Cathedral Peak research catchments in 2012. The departure point of this project was to make use of this long-term monitoring foundation provided by SAEON to show its potential, and as importantly to support it through capacity building and development of the monitoring plan for the catchments. Given this, the objective and aims of the project were developed.

The overall objective of the project was to improve the understanding of environmental change by collecting and analyzing current and historical data from the Cathedral Peak catchments, and through this refining the design for a robust and relevant monitoring network for environmental change monitoring while at the same time building capacity. Given the broad objective, the aims of this project were:

1. To compile a database of relevant historic data collected over the past 50 years from the Cathedral Peak research catchments.
2. To infill and extend the historical rainfall and streamflow record of the Cathedral Peak research catchments to the present.
3. 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.
4. To determine whether any changes in hydrological response are already evident, and to understand the underlying causes.
5. To improve the understanding of rainfall distribution across the escarpment.

6. To develop the Cathedral Peak research catchments into a living laboratory for undergraduate and postgraduate student training as well as for technical skills transfer and knowledge building.

The history of the Cathedral Peak research catchments starts in the 1930s. Over the years numerous individuals, organisation and institutions have been involved. Thus, the first aim of the project and the first task undertaken was to assemble all historical documents and data related to the hydrological history of the catchments. The compilation of the history of the catchments and the data recorded is given in Chapters 2 and 3. Once the historical data records were obtained, error checking, infilling and extension of records was undertaken. This was the second aim of the project and is addressed in Chapter 3.

As the historical and current data needs to be compatible to allow for change detection studies and both datasets need to be stored in a common facility, the data collection and management is covered in Chapter 3 together with a cross-calibration study to ensure the compatibility of the historical and current rainfall. The hydrological monitoring plan developed for the Cathedral Peak research catchments is detailed in Chapter 4. Aim 4, to determine whether any changes in hydrological responses are already evident, and to understand the underlying causes, is addressed in Chapter 5 through a change detection study on temperature, rainfall and streamflow records from the catchments for both the historical and current period of data. Chapter 6 details the work undertaken to improve the spatial understanding of the rainfall distribution across the catchments. Capacity building was a key activity throughout the project, and the activities undertaken related to this are outlined in Chapter 7.

2. CATHEDRAL PEAK RESEARCH CATCHMENTS: DESCRIPTION AND HISTORY

The Cathedral Peak research catchments have long history associated with them, beginning in the 1930s. Over the years, a number of scientifically significant hydrological and vegetation studies have taken place in the catchments. This Chapter, following a description of the research catchments, outlines the history of the catchments and reviews the hydrological studies that have made use of the data from the research catchments.

2.1 Description of the Cathedral Peak Research Catchments

The Cathedral Peak research catchments (29° 00′ S; 29° 15′ E) are located on the Little Berg plateau in the northern part of the uKhahlamba Drakensberg (Figure 2.1), a mountain range which is essential for water generation in South Africa. The fifteen research catchments, which are well defined, are situated at the head of three isolated Little Berg spurs, and range in altitude from 1 820 m.a.s.l to 2 463 m.a.s.l. All the catchments are underlain by basaltic lavas, which overlie Clarens Sandstone (Nänni, 1956). Three post-Karoo dolerite dykes, each 3 m wide, run through the research area but they are assumed to exert no hydrological influence (Nänni, 1956). The soils of the catchments are acidic, highly leached (Schulze and George, 1987) and are classified as Lateritic Red and Yellow earths, grading into heavy black soils (Katspruit and Champagne) in the saturated zones and along the stream banks (Granger, 1976). The mean soil depth in the catchments according to Schulze (1975) is approximately 0.80 m, with an A-horizon depth of 0.20 m. However, Everson *et al*. (1998) found the mean soil depth of catchment VI to be 0.50 m with an A-horizon depth of 0.25 m. In a latter study, Scott *et al*. (2000) indicated the depth of the soil profile to be at least 1.5 m with Hutton and Griffin forms occurring frequently on the gentler slopes of the catchments.

The Cathedral Peak research catchments fall within the summer rainfall region of South Africa, thus the area experiences wet, humid summers and cold, dry winters (Everson *et al*., 1998). The mean annual precipitation (MAP) for the area is approximately 1 400 mm (Bosch, 1979), with 84 % of this rainfall occurring between the months of October to March (Schulze, 1975). Half of the rainfall events in the catchments are thunderstorms (Schulze, 1975). Approximately 49 % of the rainfall is converted to streamflow, with two thirds of the streamflow yield occurring during the four months from January to April (Bosch, 1979). The long term average temperature for the catchments is 13.8°C (Everson *et al*., 1998). Although the temperature drops considerably during winter there are only occasional snowfalls in the catchments (Nänni, 1956). A summary of the catchments aspect and MAP is provided in Table 2.1.

The natural grassland of the Cathedral Peak research catchments is *Themeda triandra*, with woody communities in which *Leucosidea sericea* and *Buddleia salvifolia* predominate occurring in narrow zones along the streams in some catchments (Bosch, 1979). In Catchments II, III and VII the *Themeda triandra* grasslands were replaced with *Pinus patula* during the 1950s and 1960s, following removal of the trees the catchments were rehabilitated with *Eragrostis curvula*. The vegetation of Catchments I, IV, V, VI, VIII and X remains as *Themeda triandra* grassland. The suggested burning treatments of these catchments is given in Table 2.1. Catchment IX was a burn exclusion catchment, thus successional changes in the vegetation have taken place on the south-facing slopes where communities dominated mainly by *Themeda triandra* have been replaced by communities in which

Philippia evansii, *L. sericea* and *Pteridium aquilinum* dominate (Granger, 1976). The vegetation of Catchments XI-XV is dominated by *Themeda triandra*, however the burning regime of these catchments has varied over the years.

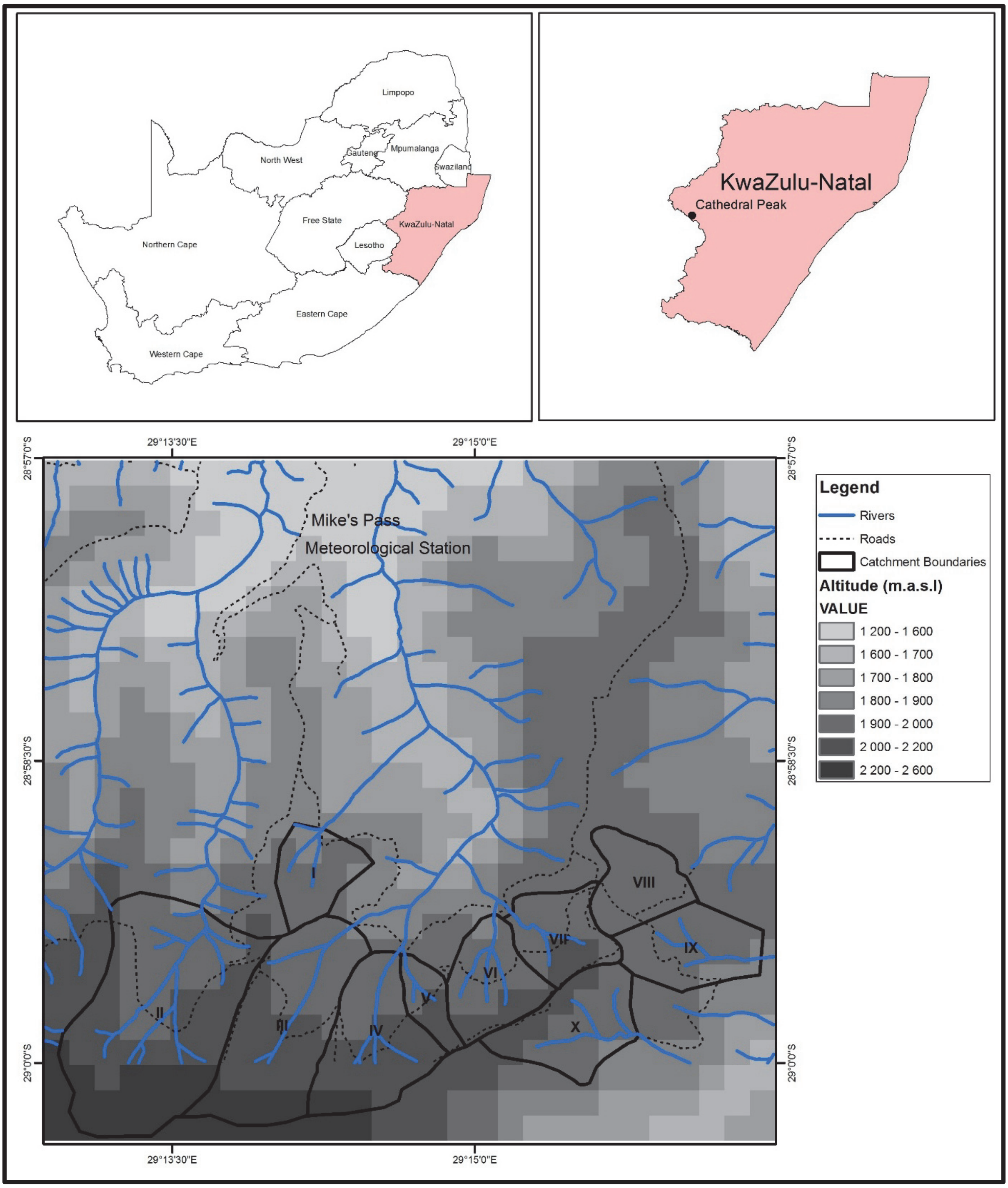

Figure 2.1: Location of the Cathedral Peak research catchments, KwaZulu-Natal, South Africa

2.2 History of the Cathedral Peak Research Catchments

Controversy around the possible negative impacts of large-scale afforestation with exotic trees on the water resources and landscape of South Africa led to the establishment of the Jonkershoek Forest Influences Research Station in 1935 (Bennet and Kruger, 2015). Christiaan L. Wicht was the first director of this station. In consultation with other senior officers, Dr I.J. Craib, the Chief Forest Research officer of the Union of Forests Department at that time, selected the Cathedral Peak research catchments as an additional site to conduct catchment investigations (Nänni, 1956; Bennet and Kruger, 2015). Craib, himself, led the reconnaissance mission in 1936 to select the sites (Bennet and Kruger, 2015). In 1938, Mike de Villiers, Wicht's assistant, was posted to Cathedral Peak to lead the establishment of the Cathedral Peak Forestry Influences Research Station (Bennet and Kruger, 2015).

Wicht played an instrumental role in the design of the catchment monitoring program. His paper "Validity of Conclusions from South African Multiple Watershed Experiments" (1967) details the evolution of ideas around the final design adopted by Dr I.J. Craib, the Chief Forest Research officer of the Union of Forests Department at that time, in consultation with other senior officers (Nänni, 1956). In addition to the Jonkershoek and Cathedral Peak catchments, Mokobulaan and Witklip in Mpumalanga and Westfalia in the Limpopo province (Nänni, 1956) were additional sites where the influences of commercial forestry were investigated (Nänni, 1956). However, the Cathedral Peak catchments remained the primary research station in the mountainous summer rainfall region of South Africa. Over the years, these catchments have been used to examine the impacts of various land management and treatment practices on hydrological responses (Everson *et al*., 1998). Initially, the primary land use of concern was commercial plantation forestry, however later on the impacts of different fire regimes as well as grazing influences were included as treatments (Nänni, 1956). By 1973 Cathedral Peak and Jonkershoek were recognised as the only truly paired catchments experiments taking place globally (Hewlett and Pienaar; in Bennet and Kruger, 2015).

Although activities in the Cathedral Peak research catchments started in 1938, work was suspended until the end of World War II in 1945. Following this, work progressed slowly until the access road from the research offices (1 372 m.a.s.l) to the research catchment (~ 1 890 m.a.s.l) was completed in 1948 (Nänni, 1956). This road was called Mike's pass after Mike de Villiers whose job it was to align and oversee construction of the road (Bennet and Kruger, 2015). Following the completion of the road, construction of the weirs and siting of the raingauges began, with measuring beginning from October 1948. Initially, ten catchments were delineated (I-X), the proposed treatments at that time for the catchments are shown in Table 2.1. By 1952, a topographic survey of the area had been completed, a botanical survey (Killick, 1963) of the area had been started and a geological survey by Pike and de Villiers, with special reference to hydrological conditions was also completed (Nänni, 1956). Over the course of the research programme the treatments were not all implemented as proposed. During March 1972 the research programme was modified. The revised treatments for the catchments are also shown in Table 2.1.

Table 2.1: Catchment characteristics and details of the proposed and actual treatments for the Cathedral Peak research catchments

Catch.	MAP (mm)	Altitude (m.a.s.l)	Aspect	Area (km^2)	Treatment proposed in 1945	Treatment post 1972-2000	Suggested treatment post 2000
I	1 406	1 822-1 989	NNE	0.487	Biennial spring burn (uneven years) and grazed conservatively until 1957. In 1959 to be planted in 1 yr to *P. patula*. To be planted and managed according to current practice.	Catchment was not planted. Light summer grazing and biennial spring burns continued post-1972. Summer grazing suspended in 1981.	Discontinued. Part of normal management burning.
II	1 680	1 845-2 454	NNE	1.900	Catchment to be planted to P. patula. To be managed according to current practice.	Planted in 1951 and maintained as *P. patula* until 1981 when clear felling and planting of *E. curvula* began.	Fire protected.
III	1 564	1 845-2 317	NNW	1.389	Biennial spring burn (uneven years) until 1957. In 1959 to be planted in 1 yr with *P. patula* and managed the same as Catch II.	Planted in 1959 and maintained as *P. patula* until 1981 when a wild fire burnt out catchment. Following fire, catchment planted to *E. curvula.*	Fire protected.
IV	1 420	1 845-2 226	NNW	0.947	Biennial spring burn (uneven years) until 1989. In 1991 to be planted in 1 yr to *P. patula* and managed according to current practice. This catchment is regarded as the main control.	Catchment remained as a grassland catchment receiving biennial spring burns.	Biennial spring burn.
V	1 393	1 845-2 073	NNW	0.265	Biennial spring burn (uneven years) until 1973. In 1975 to be planted in 1 yr to *P. patula* and managed according to current practice.	Catchment remained as a grassland catchment receiving biennial spring burns.	Biennial autumn burn.
VI	1 340	1 845-2073	NNW	0.667	Biennial spring burn (uneven years) until 1981. In 1983 to be planted in 1 yr to *P. patula* and managed the same as the other catchments.	Catchment remained as a grassland catchment receiving biennial spring burns.	Biennial autumn burn.
VII	1 340	1 845-2 012	WNW	0.446	Biennial spring burn (uneven years) until 1965. In 1967 to be planted in 1 yr to *P. patula* and managed the same as the other catchments.	Catchment planted to *P. patula* in Dec 1966. Catchment burnt accidentally during 1972, planted to grassland and protected until accidental fire in 1981. Following fire, catchment received biennial spring burns.	Burnt as annual firebreak.

VIII	1 287	1 875-1 985	ENE	0.632	Biennial spring burn (uneven years) until 1957. In 1959 to be planted in 1 yr to a Eucalypt species. Species to be determined when material in arboretum indicates best species. Management determined according to species.	Catchment was not planted. Catchment remained as a grassland catchment receiving biennial spring burns.	Discontinued. Form part of firebreak and/or part of normal scheduled burning program.
IX	1 257	1 822-1 982	ENE	0.645	This catchment is to be protected from all agencies for an indefinite period to determine the succession and its effects on water supplies.	Catchment protected from all agencies except for accidental fires in July 1954, September 1956, August 1964, and June 1965.	Fire protected.
X	1 318	1 845-2 073	SSE	0.728	Biennial spring burn (uneven years) until 1957. In 1959 to be planted in 1 yr with an alternative pine (possibly *P. pseudrostrolus* or *P. hartweggi*). To be managed according to the regime in practice at the time.	Catchment was not planted. Catchment remained as a grassland catchment receiving biennial spring burns.	Fire protected 8-year rotation (2010 was next scheduled burn).
XI	1 754	1 871-2 135	NNW	0.260	NA	Grassland catchment with a biennial spring burn while calibrating (1974-1981). From 1981, an annual winter burn. A large portion of this catchment is burnt as a firebreak.	Discontinued. Burn as part of firebreak.
XII	1 804	1 869-2 205	NNW	0.139	NA	Grassland catchment with a long-term early spring burning regime, 8 yr cycles.	Discontinued. Burnt as one block with Catchments XIII & XIV.
XIII	1 792	1 890-2 275	WNW	0.278	NA	Grassland catchment with a long-term early autumn burning regime, 8 yr cycles. Protected between cycles.	Discontinued. Burnt as one block with Catchments XII & XIV.
XIV	1 874	1 890-2 651		1.296	NA	Grassland catchment with a biennial spring burn following a period of protection.	Discontinued. Burnt as one block with Catchments XII & XIII.
XV	1 745	1 811-2 421	ESE	1.056	NA	Protected from fires.	Burnt as normal management block but on an 8-year rotation (2010 was next scheduled burn).

During the discussion surrounding the modification of the research programme it was decided to add five new gauged grassland catchments to the research programme to allow for the impacts of various burning treatments on grassland and scrub vegetation to be assessed. The streamflow gauges in these five additional catchments (XI-XV) were installed in 1975. In addition to the gauged catchments, a number of focused experiments were initiated to examine the impacts of controlled burning on grasslands and scrub vegetation (Granger, 1972). In 1988, the management of the Cathedral Peak Research catchments was handed over to the Natal Parks Board (now EKZNW) when state forest land was handed over to the provinces. The responsibility for monitoring was handed to the CSIR. Monitoring in the Cathedral Peak research catchments continued until 1995 when, due to lack of funding, monitoring in the catchments ceased (Krüger, 2012). However, EKZNW continued to fund the burning treatments until 2000 when budget constraints no longer allowed for the burning treatments to continue. Given that no funding was available and the measuring equipment was non-functional and outdated, the decision taken by EKZNW was that the prescribed burning treatments of the research Catchments I-XV would be discontinued in 2001 and that the catchments would be managed as part of the burning programme for Cathedral Peak (Krüger, 2012; Table 2.1).

Given the long term climatic and streamflow records that exist for Cathedral Peak prior to the 1990s, the catchments offer the opportunity for changes in climate and hydrological responses to be detected, monitored and analysed to allow for improved process understanding. Thus, in 2011 the SAEON Grasslands-Forests-Wetlands Node began the process of restoring monitoring in the catchments.

2.3 Review of hydrological and related studies using data (1948-1993) from the Cathedral Peak research catchments

Data gathered from the monitoring of the Cathedral Peak research catchments under various treatments has contributed significantly to hydrological understanding, in particular contributing to the understanding of the impacts of afforestation on water yield, hydrological model development and understanding the impacts of fire on streamflow. In turn, the knowledge gained has informed policy.

Research contributing to the understanding of the impacts of afforestation on water yield in the Cathedral Peak catchments was initially undertaken by Nänni. The first published paper relating to the Cathedral Peak research catchments was the paper titled “Forest hydrological research at the Cathedral Peak research station” by Nänni in the Journal of the South African Forestry Association in 1956. The paper described the characteristics of the research catchments, including the geology, soils and vegetation as well as the climatic characteristics based on the first eight years of measurements (1948-1956). The paper further outlined the research programme for the catchments, providing details on the observation techniques and the treatments to be applied in order to address the question of the effects of afforestation on water supplies in the summer rainfall region. Following on from this initial paper, Nänni (1970a) published a paper titled “The effect of afforestation on streamflow at Cathedral Peak: Report No. 1” in which streamflow data from the research catchments was used to analyse the impact of afforestation on streamflow. Nänni (1970a) compared the runoff generated from Catchment II which was planted to *Pinus patula* over the period 1951-1968 and Catchment III which was planted to *Pinus patula* in 1959 to Catchment IV which remained under grassland with a biannual spring burn. The results indicated decreases in runoff in the afforested catchments relative to the grassland catchment (Figure 2.2). From these results, Nänni (1970a) determined the potential runoff of Catchment II in comparison to actual observed runoff measured at the catchment outlet (Figure 2.3).

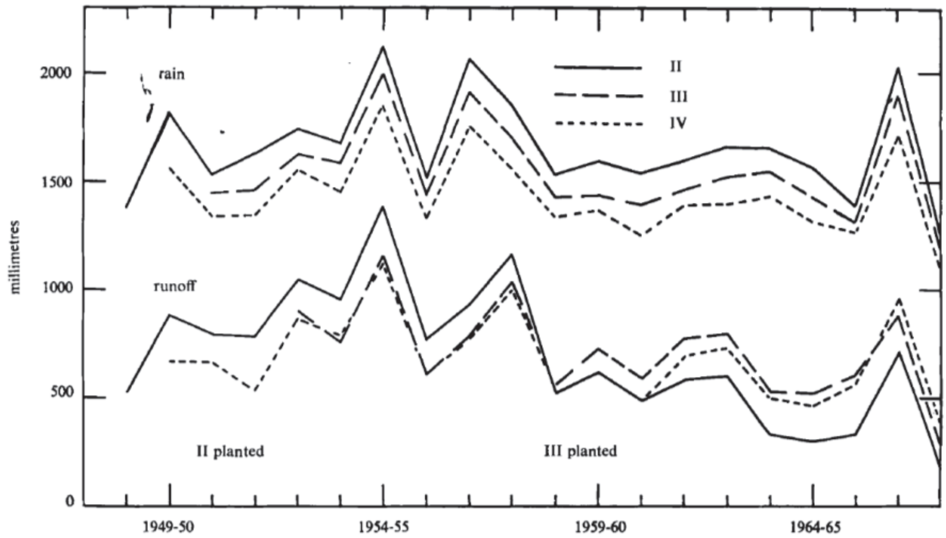

Figure 2.2: Annual rainfall and runoff from three Cathedral Peak catchments (Nänni, 1970a)

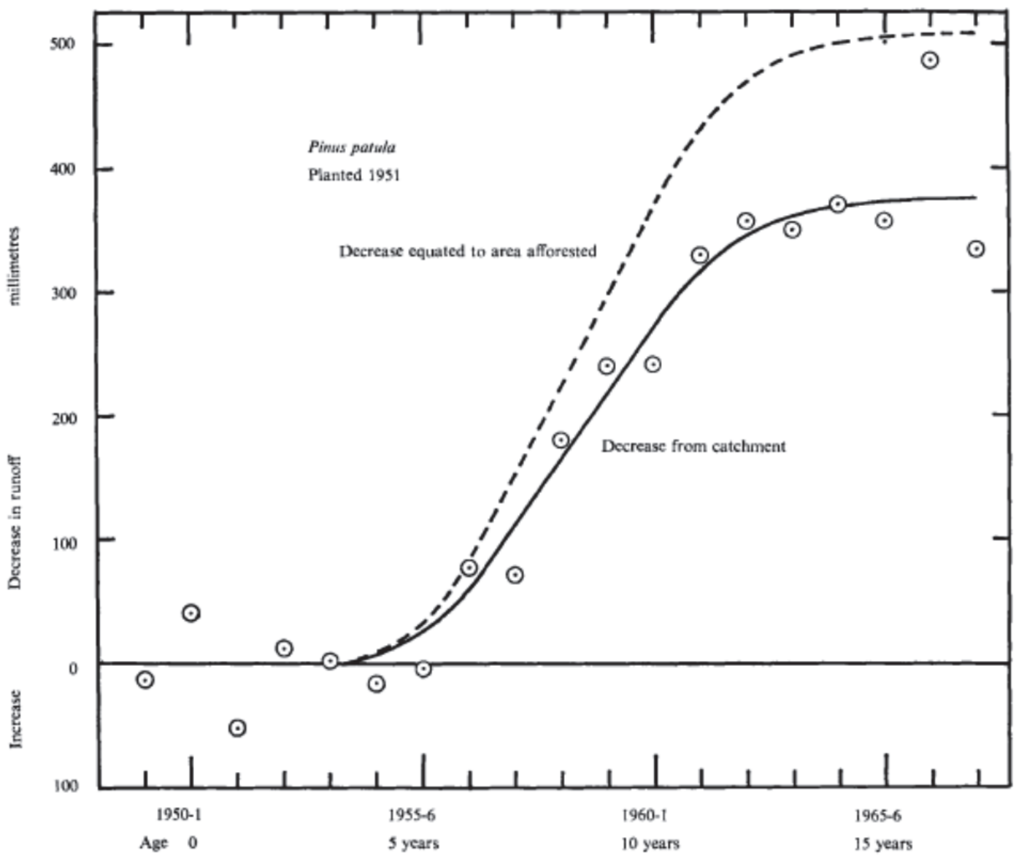

Figure 2.3: Average deviations (without trees dotted line, with trees solid line) in runoff from Catchment II, Cathedral peak due to afforestation (Nänni, 1970a)

Following on from this work, Nänni (1970b) derived curves relating the average relationship between runoff before and decrease in runoff after afforestation based on the Cathedral Peak research catchments data (Figure 2.4). These curves which became known as the "Nänni curves" were the sole determinate for whether timber growers were granted permits under the legislation known as the Afforestation Permit System (APS) which was introduced following the amendment of the Forest Act (Act No. 72 of 1968). Under the APS, timber growers were required to apply for permits to establish commercial plantations on new land or sections of land, which, after harvesting, had not been planted to trees for a period exceeding five years (van der Zel, 1995). This was the first legislation to control afforestation. Through the addition of data from the USA and elsewhere, the Nänni curves (Nänni, 1970b) were improved and became known as the "van der Zel Curves" (van der Zel, 1990). The van der Zel Curves (van der Zel, 1990) were used for APS until further developments were made in understanding the impacts of afforestation on streamflow during the 1990s. Scott and Smith (1997) developed a set of eight curves which could be used to predict the percentage reduction in the natural streamflows (total or low flows) as a function of stand age for eucalypt and pine stands in both optimal and sub-optimal growth zones. These curves became known as the CSIR curves. To develop these CSIR curves, Scott and Smith (1997) used data from the Cathedral Peak research catchments together with data from three other long-term afforestation catchment experiments.

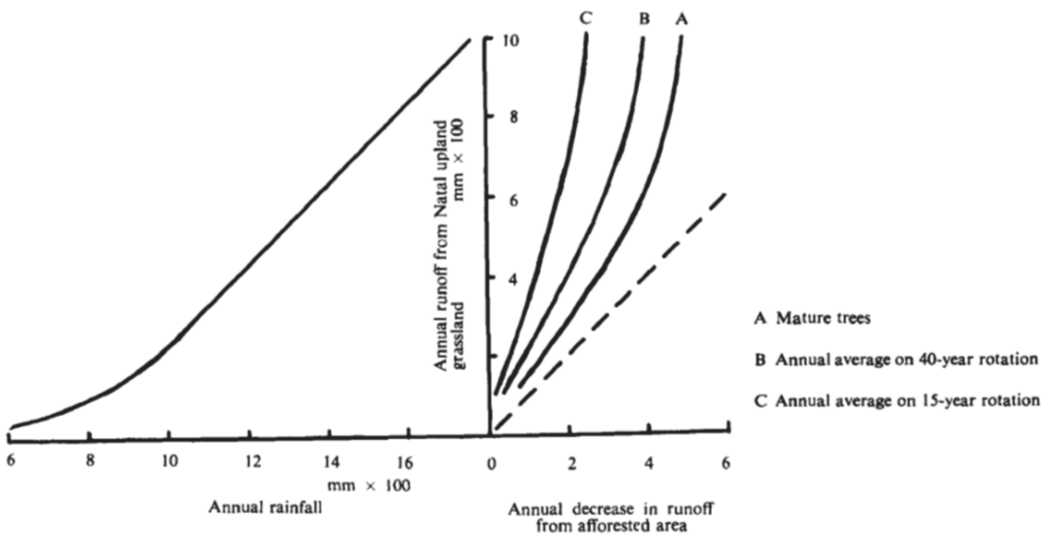

Figure 2.4: The relationship between mean annual rainfall (MAP), mean annual runoff (MAR) and the expected reduction in runoff following afforestation with *Pinus patula* of a grassland catchment (Nänni, 1970b)

With the implementation of the National Water Act of 1998, commercial afforestation was declared a streamflow reduction activity (SFRA). Under the National Water Act (1998) any SFRA required a Water Use License. Given this requirement, the shortcomings of the CSIR curves were recognised. A new approach to determining the impacts of afforestation for use in the Water Use Licensing System was undertaken by Gush *et al*. (2001) and further refined by Jewitt *et al*. (2009). Both these studies used a hydrological model to determine the impacts of afforestation, with model verification using data from the Cathedral Peak research catchments together with data from other long-term afforestation catchment experiments.

Two other key publications resulting from data from the Cathedral Peak research catchments include the paper titled “Water-use by Riparian Vegetation at Cathedral Peak” by Nänni (1972) and the paper titled “Treatment Effects on Annual and Dry Period Streamflow at Cathedral Peak” by Bosch (1979). Nänni (1972) investigated the impact on streamflow generation due to the removal of riparian vegetation from the Gogodo catchment in the Cathedral Peak research catchments area. Results indicated an increased streamflow following riparian clearing; however Nänni (1972) indicated the need for replication of the study at different sites. Bosch (1979), using an updated set of data, confirmed Nänni (1970a, b) findings that afforestation decreased streamflows, and also showed that fire suppression in grassland had no effect. Furthermore, Bosch (1979) showed that the decline in streamflow due to afforestation with *Pinus patula* is only maintained for 12 years, thereafter there is a reduction in water use by the trees.

The second area to which research undertaken using the data from the Cathedral Peak research catchments has contributed significantly is hydrological model development and related research. Using the Cathedral Peak catchments and data measurements from these catchments, Schulze (1975) developed a model for estimating catchment evapotranspiration. The model was physically-based, incorporating climatological factors (e.g. precipitation, radiation), topography, soils and made adequate provision for different vegetation characteristics (Schulze, 1975). Although the catchment evapotranspiration model was developed on the Cathedral Peak research catchments, the aim however, was to develop a general physically-based and therefore adaptable model of catchment evapotranspiration with wide potential for application (Schulze, 1975). This aim was achieved as the catchment evapotranspiration model was the building blocks for the physically-based, daily time-step *ACRU* agrohydrological model (Schulze, 1995). Related to initial work, Schulze (1976) used the dense network of raingauges in the Cathedral Peak research catchments to test the application of trend surface analysis to determine catchment rainfall. Schulze’s (1976) results indicated that trend surface analysis could be successfully used to determine long-term catchment rainfall. However, the method proved unsuccessful when deriving rainfall amounts for short-term, localised precipitation. Everson *et al*. (1998) monitored the components of the hydrological water balance of Catchment IV, a grassland catchment with one of the aims of the work being to provide a modelling framework for the catchment water balance for use in water resource management planning, and to test the reliability of existing hydrological models. The findings were that the *ACRU* model was capable of simulating the trends in observed streamflows adequately, however the ability to represent the unsaturated subsurface flow of water in the soil which was found to be an important component of the hydrology of the catchment needed improvement.

The prescribed burning treatments and the accidental wildfires that pass through the Cathedral Peak research catchments allow the impacts of fire on the hydrological responses of the catchments to be investigated. The first study to consider the impacts of fire on the streamflow of the Cathedral Peak catchments was undertaken by Nänni (1960). To determine the impacts of fire on streamflow, Nänni (1960) compared the average highest daily base-flow three days before burning and average of three days after burning for the grassland catchments (Catchments III to VII) that were burnt out during the dry seasons of 1953, 1955, 1957 and 1959. In addition, Nänni (1960) included data from an accidental fire in 1949, from two spring burns in 1951 and from two accidental fires in 1956. The results showed that fire had no significant impact on the streamflows of the grassland catchments. In a later study, Bosch *et al*. (1984) agreed with the findings of Nänni (1960) that fire did not alter total streamflows, but showed a minor change in stormflows. Following the wildfire that passed through the afforested catchments in 1981, Van Wyk (1986) documented the high sedimentation rates with at least 37 $t.ha^{-1}$ of sediment estimated in the first year post fire. Unfortunately, although large changes in streamflow were evident, these could not be quantified due to the damage caused to the weir by the excessive sedimentation. The high sedimentation rates were attributed to the high intensity fire which resulted in water repellent layers at some depth below the soil surface. Thus, infiltration capacity was negligible causing a marked increase in stormflows which carried the surface soil to the streams (Van Wyk, 1986; Scott, 1997).

Although substantial use of the data from the Cathedral Peak catchments has been made to improve hydrological understanding, there is still much that can be done. The extended data available from the reestablishment of monitoring and the platform provided for specialized field campaigns, together with the historical data offer enormous potential for advancing hydrological process understanding, leading into model development and improvement.

3. CURRENT AND HISTORICAL DATA FROM THE CATHEDRAL PEAK RESEARCH CATCHMENTS: DATA COLLECTION AND MANAGEMENT

The data collected from the Cathedral Peak research catchments is highly valuable. Given the potential uses of the data, the documentation of the metadata including the equipment used, the collection procedures, and the error checking undertaken are as important as the storage of both the historical and current data in an accessible database. This Chapter provides an inventory of the climatic and hydrological measurements and data originating from the catchments, the quality checking of the historical data that has been undertaken, and the data collection, protocols and management. The Chapter ends with a cross-calibration study that was undertaken to ensure the compatibility of the current rainfall records with the historical records.

3.1 An inventory of past measurements and data

A wealth of data has been collected for the Cathedral Peak research catchments, with the Council for Scientific and Industrial Research (CSIR) being the custodian of the hydrological and climatological datasets until SAEONs involvement in the catchments. An electronic version of the historic data for Cathedral Peak catchments (and the other research catchments) was obtained from the CSIR (with the assistance of Eric Prinsloo), by the SAEON. This dataset is referred to as "Hydrodat". It includes streamflow, weather station, rainfall and water chemistry data in raw and processed forms for the various research catchments across the country. It also contains the ACSYS program which was used to process data. The datasets are a combination of historically manually recorded data, and data recorded using Casella gauges as well as later instrumented logger data. The Hydrodat dataset that was received was not a finalised product. Not all files had been processed and a clear description of final product files was not available. An important component of this project was to decipher the status of the data within Hydrodat to identify the final product files and potentially important, but yet, unprocessed files. A number of sources of information that serve as meta data for this historic data collection have been collated and are available from the reference library at SAEON GFW.

It is important to note that beyond the climatic and hydrological data which has been documented here, there is a vast array of vegetation data including vegetation plots and fixed point photographs. This vegetation data, although captured and documented by SAEON, is beyond the scope of this project.

3.1.1 Climatic measurements

Historically there were two primary weather stations recording climatic variables for the research catchments, a station located at the top of Mike's Pass (Figure 3.1) and a climate station located near the research office. The Mike's Pass meteorological station starting recording in 1948 and continued until 1995 after which monitoring ceased due to a lack of funding. Monitoring was done manually until 1984, when automated weather stations were installed. The daily variables recorded were average temperature, average relative humidity, average solar radiation, average wind direction and average wind speed. The meteorological station at the research office started

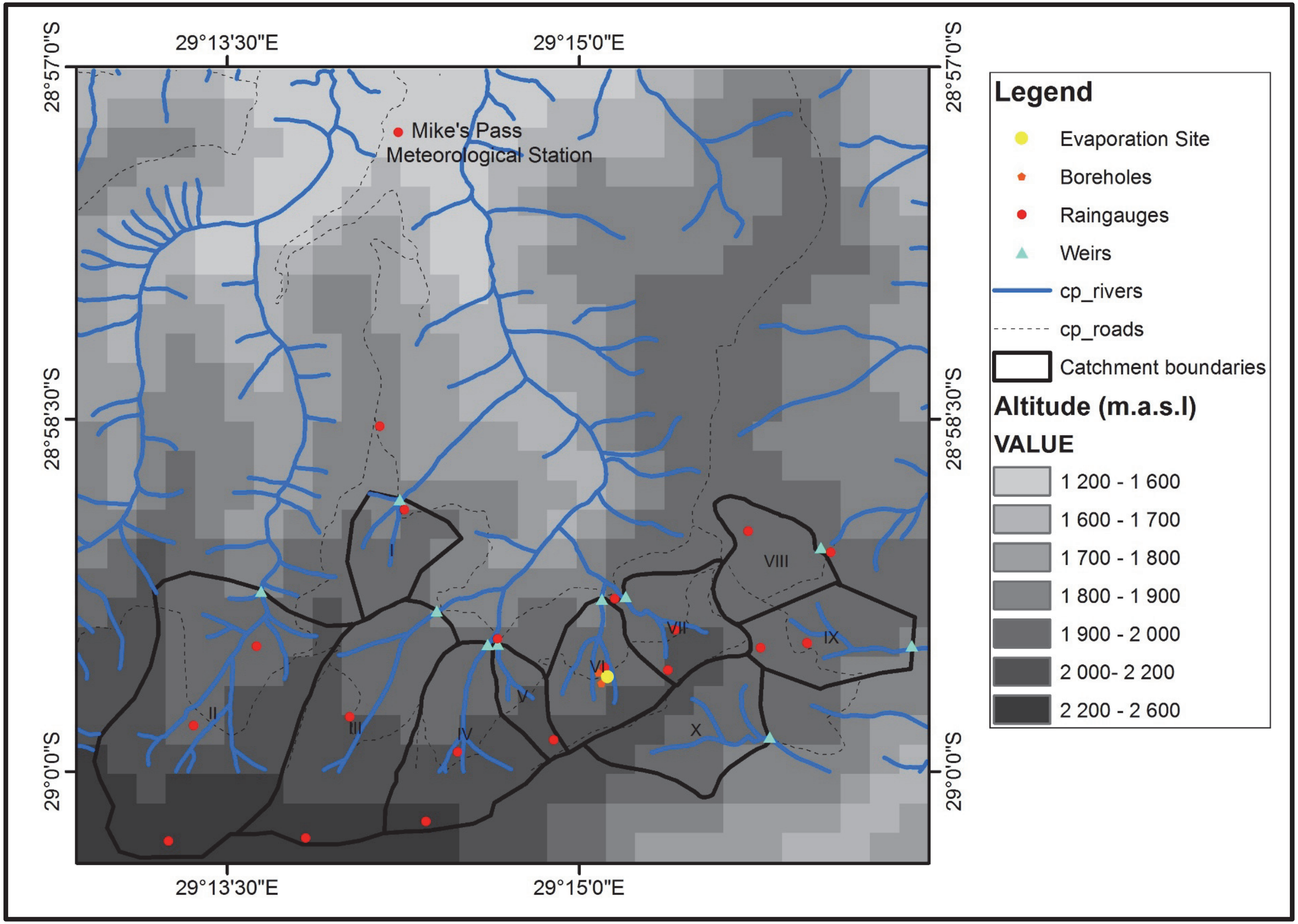

Figure 3.1: Map showing historical climatological and hydrological monitoring sites (after Schulze, 1979; Everson *et al*., 1998)

Table 3.1: Details of raingauges located in catchment I-X

Catchment	*Start date*	*End date*	*Gauge No.*	*Co ordinates*		*Elevation (m)*	*Aspect*	*Slope (% rise)*	*Gauge type*	*Read*
				Latitude	*Longitude*					
I	1 Aug 1950	1 Oct 1985	IA	-28.988	29.234	1847	North	4.078	5" Snowdon with Nipher shield inclined at 20°50'	Monthly
I	18 July 1950	1 Oct 1985	ICR	-28.981	29.237	1961	North	26.39	5 & 1/16" Casella Snowdon recording	Weekly
I	9 Aug 1973	1 Oct 1985	IBR						5 & 1/16" Casella Snowdon recording	Weekly
II	2 Aug 1948	1993	IIA	-29.005	29.222	2280	North	61.38	5" Snowdon with Nipher shield inclined at 32°00'	Monthly
II	2 Aug 1948	1993	IIC	-28.996	29.235	1870	North West	21.52	5 inclined at 13°55', Nipher shield	Monthly
II	2 Aug 1948	1993	IIBR	-28.996	29.223	1967	North East	13.85	5 & 1/16" Casella Snowdon recording	Weekly
III	1 July 1950	1 Oct 1985	IIIA	-29.005	29.232	2174	North	39.52	5" Snowdon with Nipher shield inclined at 29°55'	Monthly
III	1 Aug 1950	1993	IIIBR	-28.996	29.234	1958	East	13.54	5 & 1/16" Casella Snowdon recording	Weekly
IV	29 Sept 1949	1993	IVBR	-28.999	29.241	1943	North	12.68	5 & 1/16" Casella Snowdon recording	Weekly
IV/V	29 Sept 1949	1993	IV-V CR	-28.991	29.244	1839	North	8.87	5 & 1/16" Casella Snowdon recording	Weekly
IV	1 Oct 1949	1993	IVA	-29.003	29.238	2116	North East	41.42	5" Snowdon with Nipher shield inclined at 30°45'	Monthly
V/VI	1 Aug 1950	1993	V-VI A	-28.998	29.248	2049	North	16.23	5" Snowdon with Nipher shield inclined at 13°50'	Monthly
VI	26 Feb 1953	1993	VIBR	-28.993	29.252	1908	North	14.33	5 & 1/16" Casella Snowdon recording	Weekly
VI/VII	1 Aug 1950	1993	VI-VIIA	-28.993	29.256	1957	North West	24.96	5" Snowdon with Nipher shield inclined at 26°55'	Monthly
VI/VII	26 Feb 1953	1993	VI-VIICR	-28.988	29.253	1845	West	11.26	5 & 1/16" Casella Snowdon recording	Weekly
VII	29 Mar 1953	1 Oct 1985	VIIBR	-28.99	29.257	1904	North West	17.43	5 & 1/16" Casella Snowdon recording	Weekly
VIII	7 Oct 1965	1993	VIIIA	-28.982	29.264	1905	South East	12.81	5" Snowdon with Nipher shield	Monthly
VIII	17 Sept 1965	1 Oct 1985	VIIIBR	-28.985	29.269	1904	North	14.86	5 & 1/16"	Weekly
VIII	7 Oct 1963	1 Oct 1985	VIIIC	-28.983	29.269	1870	East	13.22	5"	Monthly
IX	1 Apr 1953	1993	IXA	-28.992	29.263	1966	East	22.17	5"	Monthly
IX	3 Jun 1954	1 Oct 1985	IXBR	-28.991	29.266	1893	East	12.21	5 & 1/16"	Weekly
IX	3 Jun 1954	1993	IXCR	-28.992	29.274	1815	South East	11.03	5 & 1/16"	Weekly
X	30 Jul 1955	1993	XA	-28.997	29.254	2034	South East	24.75	5" Snowdon with Nipher shield inclined at 17°00'	Monthly
X	30 Jul 1955	1 Oct 1985	XCR						5" Snowdon with Nipher shield inclined at 6°00'	Monthly
X	1 Jan 1973	1 Oct 1985	XB	-28.998	29.263	1837	South East	20.80	5 & 1/16"	Weekly

 # Dates given in table Obtained from Eric Prinsloo, CSIR

recording in 1952 and continued until 1993 and recorded the same variables. In addition to the meteorological stations, rainfall was also recorded at several sites in the research catchments.

In addition to these meteorological stations, precipitation was historically monitored at several sites across the catchments. There were 25 rainfall gauges located across Catchments I-X (Figure 3.1). The raingauges were labelled with a Roman numeral followed by a letter. The Roman numeral refers to the catchment number in which it is positioned and the letter to the position of the raingauge within the catchment. For each Catchment, a raingauge was located at the top of the catchment and these gauges are denoted by the letter 'A', in the middle of the catchment denoted by the letter 'B' and at the bottom of the catchment near the weir denoted by the letter 'C'. The raingauges at the top of the catchment were 5" Snowdon gauges inclined parallel to the slope, equipped with a Nipher shield and read monthly. The raingauges in the middle of the catchment and at the bottom of the catchment were Casella Snowdon 5 & 1/16" recording raingauges read weekly. Images of examples of these two types of raingauges used in the catchments is shown in Figure 3.2. Details of the record lengths of the raingauges in Catchments I-X, the type of gauges and the interval at which they were read are given in Table 3.1.

Figure 3.2: Historical raingauge types used in the Cathedral Peak research catchments, left 5" Snowdon gauge equipped with Nipher shield, right Casella Snowden 5 & 1/16" recording raingauge

In addition to the above raingauges, there were 19 gauges installed in Catchments XI-XV starting from November 1972. These gauges, except two, only recorded data until October 1985. The data for these gauges has been obtained and the date they were installed was determined from the documentation on the catchments history. Table 3.2 provides the gauge numbers and records lengths for the gauges in Catchments XI-XV.

Evaporation was measured at the Mike's Pass meteorological station until 1984 using an A-pan, after which the automated weather station was installed. In addition, a Lysimeter was installed in Catchment VI (Figure 3.1) to monitor evapotranspiration, however, there is no long term data available as there were problems with wind-drift during the time it was operational (Everson, pers.

comm. 2013). Towards the end of the monitoring period in the Cathedral Peak catchments, evaporation was continuously monitored in Catchment IV from September 1990 to June 1995 using the Bowen Ratio energy balance technique (Everson *et al*., 1998). During this period, to complete the energy balance, an automatic weather station was installed in Catchment IV. The weather station provided precipitation measurements, solar radiation, albedo, the reflection coefficient of shortwave radiation, temperature and humidity. Wind speed (2.0 m height) was measured with a cup anemometer, as well as with two 3-way anemometers (1.5 and 2.0m height) and wind direction was also monitored. The Bowen ratio system monitored net irradiance, soil heat flux density and soil temperature (Everson *et al*., 1998). The annual evaporation totals for the period monitored as taken from Everson *et al*. (1998) were 681 mm (Oct 1990-Sept 1991), 725 mm (Oct 1991-Sept 1992), 698 mm (Oct 1992-Sept 1993) and 651 mm (Oct 1993-Sept 1994).

Table 3.2: Record lengths and raingauge numbers for gauges located in Catchments XI-XV

Catchment	*Start date*	*End date*	*Gauge No.*
XI	1 Jan 1973	1993	XIC
XI	1 Jan 1973	1 Oct 1985	XIB
XII	1 Jan 1973	1 Oct 1985	XIIA
XII	1 Jan 1973	1 Oct 1985	XIIB
XIII	1 Jan 1973	1 Oct 1985	XIIIA
XIII	1 Jan 1973	1 Oct 1985	XIIIB
XIII	1 Jan 1973	1 Oct 1985	XIIIC
XIV	14 Nov 1972	1 Oct 1985	XIV G
XIV	1 Jan 1973	1 Oct 1985	XIV C
XIV	1 Jan 1973	1 Oct 1985	XIV E
XIV	1 Jan 1973	1 Oct 1985	XIVF
XIV	10 Dec 1975	1993	XIVGR
XV	15 Nov 1972	1 Oct 1985	XVE
XV	1 May 1975	1 Oct 1985	XVB
XV	1 May 1975	1 Oct 1985	XVC
XV	1 May 1975	1 Oct 1985	XVD
XV	1 May 1975	1 Oct 1985	XVF
XV	1 May 1975	1 Oct 1985	XVG
XV	29 Dec 1976	1 Oct 1985	XVER

 # Dates given in Table Obtained from Eric Prinsloo, CSIR

3.1.2 Hydrologically Related Variables

Historically the catchments have been used to examine the impacts of various land management and treatment practices on hydrological responses. Thus, streamflow was monitored for all catchments. In addition, water quality data was collected for selected catchments and sediment loads were estimated when weirs were cleaned. An intensive monitoring program was carried out in the pristine catchment VI where groundwater data, and for a short period soil water data, was also collected.

Streamflow monitoring was initiated in Catchments I-IX (Table 3.3) during the late 1940s and 1950s, Catchment X during the 1960s and in the 1970s in Catchments XI-XV. At the outlet of each catchment a concrete weir and stilling hut (Figure 3.1), with 90 degree V Notches, 18 inches deep, surmounted by 6 feet wide rectangular notches of varying depth (Meyburgh *et al.,* 1970) made of brass were installed. The stilling ponds were dug to bed rock and rock walls for the pond were constructed. The stilling ponds of the weirs were cleaned of sediments on a annual basis. The locations of the weirs are shown in Figure 3.1. Details of how early measurements were taken, error checked and processed are given in Meyburgh *et al.* (1970).

Groundwater was monitored for the 1994/1995 hydrological year for two boreholes drilled in Catchment VI. The boreholes were drilled to 0.5 m below bedrock and lined with perforated 50 mm irrigation piping. The depth of the well situated 20 m above the road through the middle of Catchment VI (Figure 3.1) was 10.5 m deep (D-02), located fairly close to this borehole but higher up in the catchment (Figure 3.1) was the deeper D-01 borehole at 22 m deep (Everson *et al*., 1998). A pressure transducer type sensor and Campbell CR21X logger were used to monitor the water table level. The water levels were verified manually each week with a modified leaf wetness sensor (Everson *et al*., 1998).

When cleaning the weirs, qualitative observations on the volume of silt removed from the weirs were made for selected catchments. From 1973 estimations of the sediment load removed from selected weirs were made. The last observations or measurements were captured in 1979 for Catchments II and III. However, for most catchments no observations were made after 1974. These observations and estimations are captured in Table 3.4.

Table 3.3: Streamflow monitoring record lengths and gauge numbers

Catchment	*Start date*	*End date*	*Gauge No.*
I	31 January 1951	1 October 1985	V1M06 (New no.: V1H006)
II	1 October 1948	15 January 1993	V1M03 (New no.: V1H003)
III	1 June 1952	16 October 1991	V1M07 (New no.: V1H007)
IV	3 October 1949	1 March 1993	V1M05 (New no.: V1H005)
V	9 August 1952	14 April 1997	V1M08 (New no.: V1H008)
VI	25 November 1954	14 April 1997	V1M22 (New no.: V1H022)
VII	15 August 1957	19 February 1993	V1M21 (New no.: V1H021)
IIX	4 October 1963	1 March 1993	V1M25 (New no.: V1H025)
IX	31 October 1954	1 March 1993	V1M23 (New no.: V1H023)
X	25 September 1965	2 October 1985	V1M24 (New no.: V1H024)
XI	17 September 1975	2 October 1985	V1M42 (New no.: V1H042)
XII	17 September 1975	2 October 1985	V1M43 (New no.: V1H043)
XIII	26 March 1976	1 March 1993	V1M44 (New no.: V1H044)
XIV	17 September 1975	1 March 1993	V1M45 (New no.: V1H045)
XV	17 September 1975	18 December 1992	V1M46 (New no.: V1H046)

 # Dates given in Table Obtained from Eric Prinsloo, CSIR

Water chemistry sampling was initiated in Cathedral Peak in 1981. This was part of a bigger water chemistry study initiated by D.B van Wyk in 1971 in other research catchments in the country (see Lesch report 1992 for details). Samples taken from Cathedral Peak were sent to Pretoria and analysed by the Hydrological Research Institute. Samples were analysed for Na^+, K^+, Ca^+, Mg^+, Cl^-, SO_4^{2-}, and HCO_3. From 1982, the samples were also analysed for NH_4^+, PO_4^{3-}, NO_3^-, TP (Total Phosphorus), KN, Si and F. The pH and conductivity levels were assessed on site. From November 1981 to May 1982, the pH of the flows exiting Catchments I-VX was measured. Following this, from June 1982 until September 1985, the pH of the flows exiting Catchments I, V, VIII, X and XV was measured while from October 1985 until June 1991, the pH of the flows exiting Catchments II, III, IV, VI and VII was measured. The data are stored in the Hydrodat set from CSIR. The data processing and storage meta data is provided by Lesch (1992). Precipitation chemistry was initiated using a bulk sampler in 1984.

3.1.3 Fire Records

Fire has been demonstrated to have a significant impact on hydrological responses (Bosch *et al*., 1984; Adams *et al*., 2013). Thus, for detection and process studies using the streamflow records it is important to have fire records for the catchments. The burning treatments for the Catchments are given in Table 2.1. From the historical records for the catchments and the EKZNW fire records, the dates of when the Catchments were burnt was captured and are provided in Appendix A for Catchments I-X, and Appendix B for Catchments XI-XV. The dates of burning were verified in a desktop study.

Table 3.4: Sediment observations and estimations

Year	***Catchments***									
	I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**
1953		No comment.	Moderate silt							
1955	Little silt		Large amount of silt.	Little silt.	Large amount of silt.					
1956		No comment.		Little silt.	Little silt.	No comment.	No comment.		Almost silted up.	
1957		No comment.	Little silt.	Little silt.	Large amount of silt.	No comment.	Little silt.		Little silt.	Large amount of silt.
1958	Almost silted up.	No comment.	Large amount of silt.	No comment.	No comment.	No comment.	No comment.		No comment.	No comment.
1962	Almost silted up.	Considerable amount of silt.			Moderate silt					
1963	Large amount of silt and sand	Large amount of silt.	Large amount of silt.	Less silt than II & III.	Little silt.	No comment.	Little silt.		Little silt.	Water weeds removed.
1965		No comment.	Little silt.	Gravel delta formed at top of weir.	Little silt.	No comment.	Little silt.	Very little silt.	Est. 150m^3 silt removed.	No comment.
1966		No comment.	No comment.	No comment.	No comment.	No comment.	No comment.	No comment.		No comment.
1970	Completely silted up. Excessive gritty deposits, very little fine silt.	Dam was partly silted up.	Excessive fine, black silt removed.	Fair amount of fine black silt removed.	Little silt.	Excessive fine sludgy silt.	Fair amount fine blackish silt.	Excessive fine black silt, fair amount of grit and weeds.	No excessive silt, course pebbles, small amount of water weed.	Excessive fine silt and water weeds.
1971	Moderate silt. Mainly sand, coarse sand at inlet and fine silt towards the wall.			Not much silt.				Mainly weeds.	Mainly weeds.	
1972	Moderate silt.		Moderate silt.				No comment.	No comment.	No comment.	No comment.
1973	Total silt = 74.211m^3 or 1.48m^3.ha.yr^{-1}. Approx. 55m^3 coarse gravel, remainder fine silt.	Total silt = 143006m^3 or 0.217m^3.ha.yr^{-1}. Approx. 24m^3 coarse gravel, remainder fine silt.		Total silt = 63.54m^3 or 0.32m^3.ha.yr^{-1}. Approx. 13m^3 coarse gravel, remainder fine silt.	Total silt = 38.37m^3 or 0,35m^3.ha.yr^{-1}. Approx. 5m^3 coarse gravel, remainder fine silt.	Total silt = 56.8m^3 or 0.25 m^3.ha.yr^{-1}. Approx. 9m^3 coarse gravel, remainder fine silt.				

1974		Total silt = 148.5m^3 or 0.78 m^3.ha.yr^{-1}. Coarse gravel constituted over half of the total deposited.							Total silt = 48.1m^3 or 0.39 m^3.ha.yr^{-1}	Total silt = 22.7m^3 or 0.15 m^3.ha.yr^{-1}
1975			Total silt = 25.4m^3 or 0.37 m^3.ha.yr^{-1}	No comment.						
1976		Total silt = 142.6m^3 0.53 m^3.ha.yr^{-1}.								
1977			Total silt = 68.7m^3 or 0.24 m^3.ha.yr^{-1}							
1978		Total silt = 125.6 m^3 or 0.33m^3.ha.yr^{-1}. Silt ~ 15cm deep remains after cleaning, only measure accumulative silt.	Total silt = 28.71m^3 or 0.21m^3.ha.yr^{-1}							
1979		Total silt = 75,06m^3 or 0,385 m^3.ha.yr^{-1}	Total silt = 30,365m^3 or 0.22 m^3.ha.yr^{-1}							

3.2 Quality Control of the Rainfall and Streamflow Historical Data

Historical records contain systematic and random errors. Systematic errors may be due to the individual gauges itself or errors introduced by spatial and elevation variations in the case of raingauges or the ratings curve in the case of streamflow. Random errors include measurement mistakes and representativeness of the gauge of its surroundings (Bennet *et al*., 2008). Thus, datasets need to be carefully checked prior to use. Missing records are one of the largest problems with regards to data, thus this project infilled and where possible extended the records.

3.2.1 Methodology used for error checking and infilling of rainfall data

The type of raingauge used and recording frequencies of the historical raingauges sited in the Cathedral Peak catchments varied. Recordings were made on an hourly, daily, weekly as well as a monthly basis. To error check the records, the first step taken was a graphical analysis of the historical data records. This showed that a number of monthly records were missing or incomplete (Figure 3.3). Following this, the historical rainfall records were error checked by comparing neighbouring and similar gauges to flag any outliers, *i.e*. where a station recorded no rainfall while neighbouring or similar gauges recorded rainfall, and where a station recorded an event substantially larger than surrounding and similar stations.

Given the missing records and the flagged errors, the historical rainfall records needed to be infilled. Infilling of missing rainfall data has been extensively investigated (Bennet *et al*., 2008), with several methods available. The most common approaches to infilling of rainfall data involves the use of the closest raingauge or the weighted average of the nearby gauges to infill the missing rainfall data. In areas with complex topographic and orographic effects on rainfall, the use of distance as the only variable to select a station may be biased. Using gauges which are well correlated to infill allows the optimal selection of gauges based on their relationship to each other not simply distance apart. Thus, five rainfall infilling techniques were investigated to determine the best suited technique to use to infill the Cathedral Peak historical rainfall records. The performance of the five methods was compared using three error statistics, namely root mean square error (RMSE), mean bias, Nash-Sutcliffe model efficiency coefficient (NSE) and correlation.

Method 1: Nearest Neighbour by Distance (ND)

The Nearest Neighbour by Distance method selects the closest gauge with data to be used to infill a stations missing records. For each of the 22 historical Cathedral Peak gauges, the nearest gauge by distance (m) was determined (Table 3.5). Following this, linear regression was used to develop an equation to estimate the rainfall for the reference gauge from the rainfall from the nearest gauge. An example of a linear regression analysis is shown for reference gauge IC in Figure 3.4.

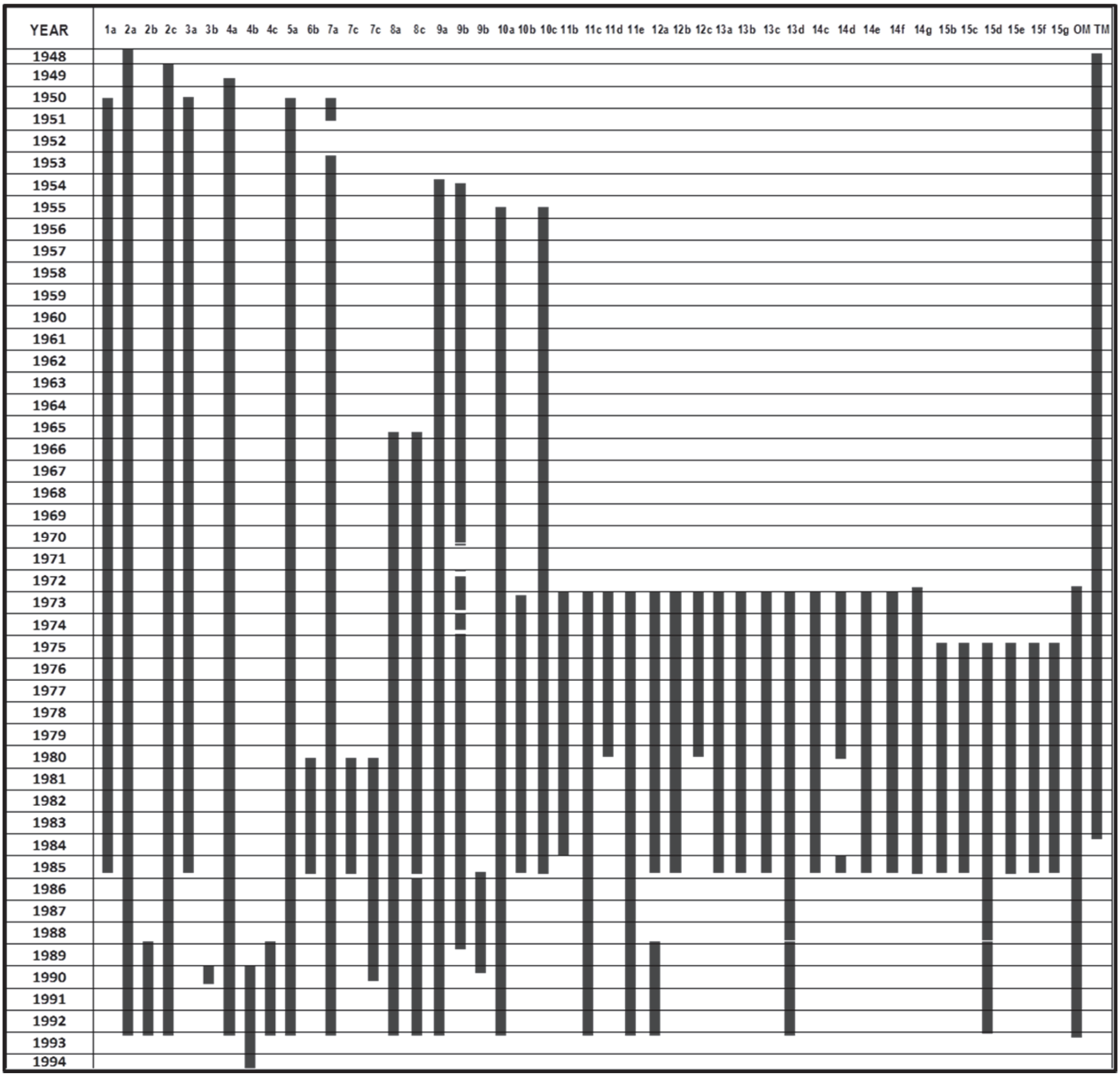

Figure 3.3: Graph showing available and missing rainfall records for each of the historical Cathedral Peak gauges (1948-1994)

Table 3.5: Distance from reference gauge to the nearest gauge in meters

REFERENCE GAUGE	NEAREST GAUGE	DISTANCE (m)	REFERENCE GAUGE	NEAREST GAUGE	DISTANCE (m)
Met Station	IC	677.08	VIB	VIIA	465.89
IC	Met Station	677.08	VIIA	VIIB	339.06
IIA	IIB	923.43	VIIB	VIIA	339.06
IIB	IIC	759.66	VIIC	VIIB	502.71
IIC	IIB	759.66	VIIIA	VIIIC	597.37
IIIA	IVA	892.09	VIIIC	VIIIA	597.37
IIIB	IVB	785.41	IXA	IXB	326.89
IVA	IVB	582.21	IXB	IXA	326.89
IVB	IVA	582.21	IXC	IXB	712.01
IVC	VIB	801.64	XA	VIB	511.19
VA	XA	566.12	XC	IXA	760.93

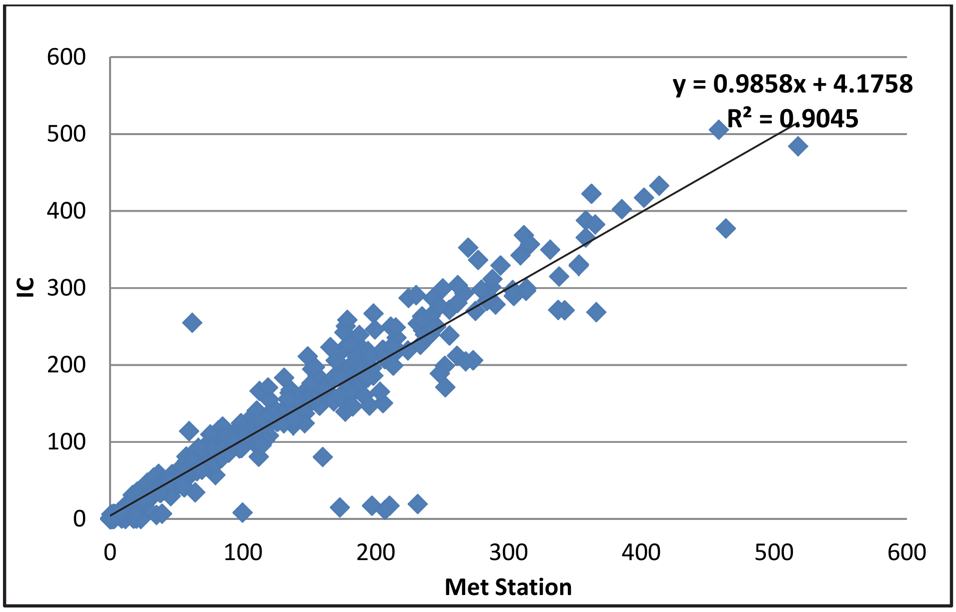

Figure 3.4: Linear regression analysis for reference raingauge IC and its nearest neighbour, the Mike's Pass meteorological station for the period 01/08/1950-01/03/1984

Method 2: *Nearest Neighbour by Correlation (NC)*

The Nearest Neighbour by Correlation method selects the neighbouring gauge that has the highest correlation with the gauge to be patched. A correlation analysis between each gauge allows for the selection of the highest correlated raingauge. The correlation results between each of the Cathedral Peak gauges is presented in Table 3.6. For each reference gauge, the closest gauge with the highest correlation is selected and a linear regression equation to infill values of the reference gauge is derived.

Table 3.6: Correlation analysis between each of the historical gauges

GAUGE	IC	IIA	IIB	IIC	IIIA	IIIB	IVA	IVB	IVC	VA	VIB	VIIA	VIIB	VIIC	VIIIA	VIIIC	IXA	IXB	IXC	XA	XB	XC
IC																						
IIA	0.964																					
IIB		0.904																				
IIC	0.948	0.940	0.993																			
IIIA	0.973	0.987		0.953																		
IIIB		0.987	0.984	0.996																		
IVA	0.977	0.971	0.990	0.957	0.993	0.983																
IVB		0.596	0.615	0.601		0.112	0.637															
IVC		0.877	0.980	0.977		0.961	0.987	0.604														
VA	0.980	0.958	0.982	0.956	0.984	0.969	0.989	0.572	0.986													
VIB	0.726	0.700		0.953	0.733		0.696			0.702												
VIIA	0.977	0.949	0.970	0.949	0.975	0.913	0.980	0.564	0.971	0.989	0.710											
VIIB	0.726	0.700		0.950	0.731		0.698			0.704	0.997	0.713										
VIIC	0.717	0.774	0.777	0.947	0.714	0.672	0.832	0.988	0.835	0.844	0.963	0.854	0.966									
VIIIA	0.896	0.884	0.969	0.974	0.899	0.941	0.919	0.538	0.978	0.932	0.950	0.933	0.955	0.968								
VIIIC	0.804	0.765	0.711	0.854	0.805	0.794	0.805	0.369	0.750	0.813	0.991	0.813	0.996	0.963	0.872							
IXA	0.976	0.944	0.969	0.944	0.976	0.912	0.978	0.541	0.979	0.988	0.691	0.992	0.696	0.839	0.934	0.818						
IXB	0.938	0.914	0.775	0.942	0.939		0.943		0.981	0.949	0.863	0.950	0.863	0.924	0.960	0.852	0.957					
IXC		0.651	0.573	0.847		0.162	0.846	0.928	0.668	0.871		0.884		0.914	0.901	0.879	0.867	0.932				
XA	0.977	0.950	0.966	0.949	0.981	0.961	0.985	0.556	0.976	0.993	0.714	0.994	0.714	0.848	0.933	0.818	0.989	0.948	0.883			
XB	0.978	0.973		0.898	0.980		0.980			0.982	0.755	0.984	0.760	0.743	0.889	0.888	0.990	0.953		0.983		
XC	0.926	0.916		0.973	0.929		0.927			0.935	0.991	0.936	0.994	0.957	0.980	0.882	0.936	0.944		0.940	0.895	
MET Sta.	0.951	0.939		0.964	0.945		0.947			0.955	0.911	0.954	0.908	0.904	0.951	0.841	0.955	0.955		0.950	0.911	0.951
MAX	0.980	0.987	0.993	0.996	0.993	0.983	0.989	0.988	0.986	0.993	0.997	0.994	0.996	0.968	0.980	0.888	0.990	0.955	0.883	0.983	0.911	0.951
MIN	0.717	0.000	0.573	0.601	0.714	0.112	0.637	0.369	0.668	0.702	0.691	0.713	0.696	0.743	0.872	0.818	0.867	0.932	0.883	0.940	0.895	0.951
AVERAGE	0.908	0.870	0.875	0.925	0.899	0.762	0.884	0.629	0.903	0.897	0.867	0.910	0.872	0.895	0.927	0.854	0.949	0.946	0.883	0.958	0.903	0.951

Method 3: Inverse Distance Weighted (IDW)

The Inverse Distance Weighted method uses multiple neighbouring gauges weighted by distance to infill rainfall values for the reference gauge, as described by

$$P_c = \frac{\sum P_i \, d_{ci} - k}{\sum d_{ci} - k}$$

Eq. 3.1

Where,

- P_c is rainfall for the gauge to be patched,
- P_i is rainfall of a neighbouring gauge,
- d_{ci} is the distance between the gauges, and
- k is a weight known as the friction distance.

The three nearest gauges by distance were determined (Table 3.7). Thereafter, a cluster analysis (Figure 3.5) was used to determine the most related rainguages in terms of MAP and altitude (m). For each reference gauge, a gauge to be used to infill missing values was selected based on a comparison between the three nearest gauges and three most related gauges to the reference gauge. Results for the comparison are shown in Table 3.7. In some cases, the gauges that were related in terms of MAP and altitude were those closest to the reference gauge. However, in most instances this was not the case and then the gauge selected was the closest, most related gauge.

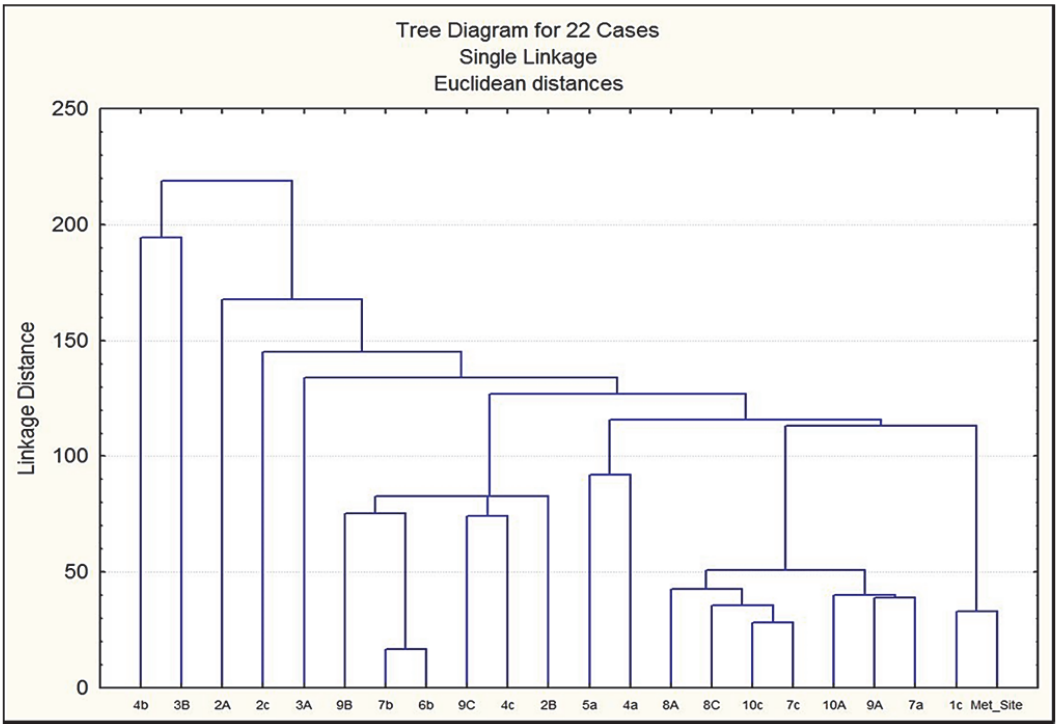

Figure 3.5: Cluster analysis for historical raingauges based on MAP (mm) and Altitude (m)

Table 3.7: Nearest gauges, closest correlated gauges and distances, selected gauge

Reference gauge	Nearest gauge	Distance to nearest gauge (m)	Correlated gauges based on MAP & altitude	Distance to correlated gauge(m)	Selected gauge
Met Station	IIC	1930.47	XA	2990.55	IC
	IC	677.08	IC	677.08	
	IVC	1885.95	IXA	3158.49	
IC	IIC	1485.29	VIIA	2258.38	Met site
	IVC	1225.25	IXA	3158.49	
	MET	677.08	Met site	677.08	
IIA	IIIA	948.47	VIB	3288.64	IIC
	IIIB	1587.90	VIIB	3874.67	
	IIB	923.43	IIC	1646.61	
IIB	IIA	923.43	IVA	1817.93	IVA
	IIC	759.66	IVC	2172.26	
	IIIB	1080.77	VA	2492.85	
IIC	IIB	759.66	IIA	1646.61	IIIA
	IC	1485.29	IIIA	1545.32	
	IIIB	849.71	IXB	3813.93	
IIIA	IIA	948.47	IIC	1545.32	IIA
	IVA	892.09	IIA	948.47	
	IIIB	1000.78	IXB	3797.67	
IIIB	IVB	785.41	IIA	1587.90	IIC
	IIIA	1000.78	IIC	849.71	
	IIC	849.71	IIIA	1000.78	
IVA	IIIB	1002.08	IIB	1817.93	VA
	IIIA	892.09	VA	1035.13	
	IVB	582.21	VIIIA	3155.33	
IVB	VA	671.83	IIA	2118.26	IIIB
	IIIB	785.41	IIC	1606.84	
	IVA	582.21	IIIB	785.41	
IVC	IVB	870.04	VIB	801.64	VIB
	VA	879.17	IXB	2172.55	
	VIB	801.64	IXC	2874.18	
VA	IVB	671.83	IIB	2492.85	IVC
	XA	566.12	IVA	1035.13	
	VIB	644.93	IVC	879.17	
VIB	VIIA	465.89	VIIB	595.09	VIIB
	VIIC	582.08	IXB	1427.61	
	XA	511.19	IXC	2108.05	
VIIA	XA	531.00	IC	2258.39	XA
	VIB	465.89	IXA	650.60	
	VIIB	339.06	XA	531.00	
VIIB	VIIC	502.71	IVC	1261.27	VIB
	VIB	595.09	VIB	595.09	
	VIIA	339.06	IXC	1629.97	
VIIC	VIIB	502.71	VIIIA	1090.02	VIIIA
	VIIA	714.36	VIIIC	1563.30	
	VIB	582.08	XC	1533.28	
VIIIA	VIIIC	597.37	VIIC	1090.02	VIIIC
	VIIB	937.22	VIIIC	597.37	
	IXA	922.79	XC	1682.02	
VIIIC	IXB	732.44	VIIIA	597.37	VIIIA
	IXA	895.31	XC	1587.89	
	VIIIA	597.37	VIIC	1563.34	
IXA	VIIA	650.60	VIIC	1095.17	VIIA
	VIIB	604.20	VIIA	650.60	
	IXB	326.89	XA	1103.25	
IXB	IXA	326.89	VIB	1427.61	IXC
	IXC	712.01	VIIB	919.72	
	VIIIC	732.44	IXC	1629.97	
IXC	IXA	1028.38	IVC	2874.18	VIIB
	IXB	712.01	VIB	2108.05	
	VIIIC	1006.12	VIIB	1629.97	
XA	VIB	511.19	VIIA	531.00	VIIA
	VA	566.12	IXA	1103.25	
	VIIA	531.00	MET	2990.55	
XC	IXA	760.93	VIIC	1533.28	VIIC
	VIIA	828.60	VIIIA	1682.02	
	IXB	860.54	VIIIC	1587.89	

Method 4: Average of Gauges Selected by Correlation (A):

The average of gauges selected by correlation method selects, for each reference gauge, the two gauges mostly closely correlated to the reference gauge. The monthly precipitation for the selected gauges is averaged and used to estimate the value for the reference gauge.

Method 5: Weighted Average of Gauges Selected by Correlation (WA):

The Weighted Average of gauges selected by correlation method selects for each reference gauge, the two gauges mostly closely correlated to the reference gauge. The monthly rainfall for each gauge are averaged weighted by the correlation level

$$\boldsymbol{P_c = \frac{\sum P_i \, . \, r_{ci}}{\sum r_{ci}}}$$

Where Eq. 3.2

- r_{ci} is the Pearson correlation coefficient for the two gauges found by:

$$\boldsymbol{r_{ci} = 1/(n_{sc} . s_i . \sum (P_{ik} - P_i) . (P_{ck} - P_c)}$$

Where Eq. 3.3

- *P* is the average rainfall for the time series,
- *s* is the standard deviation, and
- *n* is the length of the time series

The results from the rainfall patching methods are shown for all gauges in Table 3.8. A comparison between the methods indicated that for most gauges, the Nearest Neighbour by Correlation method had the smallest error (RMSE), the least variation from the means (mean bias), and the highest NSE results. However, for selected gauges the correlation results indicate that the Average of Gauges Selected by Correlation (A) method performed better. The IDW, WA and A methods had the lowest accuracy for all gauges. Given the results obtained the Nearest Neighbour by Correlation method was used to infill missing values. These values infilled values will have a flag in the SAEON database.

Table 3.8: Results of statistical analysis of five infilling methods

GAUGE	RMSE					MEAN BIAS (mm)					NSE					CORREL				
	ND	NC	IDW	A	WA	ND	NC	IDW	A	WA	ND	NC	IDW	A	WA	ND	NC	IDW	A	WA
IC	33.95	21.06	35.95	19.91	45.77	-4.89	0.00	1.23	19.58	-6.17	0.91	0.96	0.83	0.57	0.57	0.95	0.98	0.94	0.98	0.94
IIA	59.83	20.57	78.95	39.21	114.10	-0.36	-0.21	-50.25	-23.22	-85.31	0.98	0.98	0.43	0.84	-0.05	0.90	0.99	0.92	0.97	0.87
IIB	14.08	14.08	33.68	27.28	321.12	0.00	0.00	86.54	107.73	272.00	1.00	0.99	-0.26	-0.94	-0.46	0.99	0.99	0.98	0.99	0.99
IIC	13.30	5.73	50.66	32.10	91.96	0.00	0.00	-9.45	-43.17	-170.9	1.00	1.00	0.80	0.50	-0.59	0.99	1.00	0.90	0.98	0.86
IIIA	14.26	14.26	18.89	28.43	404.86	0.00	-0.02	33.63	8.31	324.1	0.99	0.99	0.52	0.55	0.19	0.99	0.99	0.99	0.99	0.95
IIIB	53.17	9.77	17.11	15.24	15.22	0.00	0.00	121.65	109.63	74.85	0.99	1.00	-0.79	-0.80	-0.88	0.11	0.98	1.00	0.97	0.96
IVA	79.44	35.39	47.64	21.69	62.92	0.00	0.19	-35.83	-13.23	-48.67	0.95	0.90	0.65	0.90	0.43	0.64	0.95	0.97	0.99	0.95
IVB	113.93	122.44	122.32	37.09	37.05	0.00	18.19	33.14	79.52	59.25	0.77	0.89	-0.07	-0.34	-0.28	0.64	0.72	0.24	0.98	0.99
IVC	74.14	16.94	64.72	19.34	18.49	3.75	0.00	9.99	96.58	85.59	0.99	0.00	0.62	-0.84	-0.63	0.73	0.99	0.94	0.98	0.98
VA	11.99	21.09	88.58	15.36	30.61	0.00	0.00	-61.46	-12.13	-18.51	0.99	0.97	0.03	0.88	0.81	0.99	0.98	0.86	0.99	0.96
VIB	56.29	11.44	15.05	9.30	9.29	-3.79	0.14	11.20	90.70	47.23	0.96	0.98	0.96	-0.60	0.26	0.76	0.99	0.99	1.00	1.00
VIIA	66.23	14.75	40.97	17.96	27.64	0.00	0.00	-11.79	14.25	5.90	0.91	0.98	0.85	0.82	0.82	0.71	0.99	0.92	0.99	0.96
VIIB	57.39	8.36	35.78	10.88	8.66	-3.86	0.13	-1.05	92.02	47.03	0.96	0.99	0.97	-0.63	0.27	0.76	1.00	1.00	0.99	1.00
VIIC	8.09	24.42	40.34	22.87	49.15	2.65	0.00	53.03	76.84	53.16	1.00	0.94	0.02	-0.35	-0.06	1.00	0.97	0.94	0.97	0.91
VIIIA	51.38	19.28	44.74	20.66	46.17	-1.75	0.00	-11.93	32.20	11.15	0.82	0.98	0.81	-0.06	0.03	0.85	0.98	0.90	0.97	0.88
VIIIC	49.89	41.91	50.32	13.41	38.68	1.82	0.05	-4.01	-182.0	-231.6	0.81	0.90	0.81	0.12	0.01	0.87	0.88	0.89	0.98	0.76
IXA	49.80	15.22	27.32	15.08	56.24	-1.72	0.00	-9.86	-3.63	-34.77	0.80	0.98	0.86	0.98	0.62	0.87	0.99	0.97	0.99	0.89
IXB	22.67	27.54	39.09	32.71	43.26	0.00	0.00	-292.2	40.46	1.25	0.97	0.95	-0.19	0.36	0.57	0.96	0.94	0.59	0.96	0.89
IXC	69.46	48.23	58.12	43.28	59.58	-14.21	-4.08	-0.39	94.09	60.11	0.98	0.97	0.78	-0.73	-0.21	0.78	0.88	0.73	0.91	0.87
XA	57.49	30.87	481.77	13.44	55.77	3.35	0.00	350.40	23.39	-20.69	0.92	0.92	0.19	0.63	0.56	0.76	0.95	0.99	0.99	0.88
XC	30.75	28.81	38.09	24.98	43.14	-0.63	0.03	-31.66	48.29	3.95	0.92	0.93	0.01	0.22	0.41	0.94	0.95	0.91	0.98	0.93
MET	31.70	27.14	45.20	23.43	47.94	0.00	0.00	-0.63	20.24	3.11	0.93	0.94	0.82	0.53	0.42	0.95	0.96	0.95	0.97	0.90

3.2.2 Methodology used for extending and infilling of streamflow records

To date the weirs at the outlets of Catchments IV, V, VI and VII are monitoring streamflow again, and the weir at the outlet of Catchment III has been cleaned and monitoring will resume in 2016. Furthermore, it is planned that the weir at the outlet of Catchment IX will be cleaned and monitoring will resume. Thus, the error checking and extension of streamflow records has focused on these catchments. Daily historical streamflow data between 1949 and 1993 (Table 3.9) was obtained for the six gauges and the data was graphed to check for outliers and anomalies. Besides missing records, no outliers or anomalies were found. Using hydrological modelling and the rainfall records from nearby stations, it is possible to extend the streamflow records.

Table 3.9: Details of the historical streamflow data obtained and used

Catchment	Streamflow record		
	Start date	**End date**	**Length (yrs)**
III	May 1952	Oct 1990	39
IV	Jan 1949	Dec 1987	38
VI	Nov 1960	Oct 1985	25
VII	Oct 1957	Feb 1993	36
IX	Oct 1954	Mar 1993	39

The physical-conceptual ACRU agrohydrological model (Schulze, 1995) was selected to model the streamflows for the catchments as the model has been shown previously to simulate the streamflows for the Cathedral Peak area adequately (e.g. Gush *et al*., 2001; Jewitt *et al*., 2009). The catchments were delineated using 1:50 000 topographic maps sheets and geographic coordinates of key points such as the weir locations. The catchment areas and average altitude were obtained (Table 3.10). The daily rainfall records from the raingauges sited within the catchments were used as were the rainfall records for the South African Weather Services station 0299357W (located near the Cathedral Peak Hotel). Daily temperature records for the South African Weather services (SAWS) gauge and from the meteorological station at Mike's Pass. In addition, gridded climate data including mean monthly minimum and maximum temperatures, mean monthly A-pan evaporation and mean monthly rainfalls were obtained from Schulze *et al*. (2008), these mean monthly values are given in Appendix C. Soils characteristics and information required as input for ACRU model for the catchments were also obtained from Schulze *et al*. (2008), these values are provided in Appendix C. The dominant vegetation cover of the grassland catchments (IV, V, VI and VII) was identified as *Themeda triandra* known as Acocks Veld Type (1988) Highland and Dohne Sourveld (Acocks Veld number 44), the vegetation parameters used as input to the hydrological model are given in Appendix C. The vegetation of Catchment III was initially set to *Pinus patula* and later to degraded grassland. Catchment IX was modelled as thicket. The critical stormflow generating depth was set to the depth of the A-horizon and the quick flow response fraction was set to 0.30.

Table 3.10: Catchment III, IV, VI, VII and IX attributes

Catchment	Area (km^2)	Altitude (m.a.s.l)	MAP (mm)	Weir longitude	Weir latitude	Mean slope (%)
III	1.389	2317.0	1564.00	29°14'18.00"E	28°59'23.00"S	38.00
IV	0.98	2010.8	1263.73	29°14'37.68"E	28°59'26.52"S	32.57
VI	0.62	1929.7	1134.00	29°15'06.84"E	28°59'16.08"S	25.08
VII	0.54	1930.4	1102.91	29°15'10.08"E	28°59'15.00"S	18.96
IX	0.645	1982.0	1257.00	29°16'25.00"E	28°59'29.00"S	22.00

The model was initially set-up and run with the rainfall records of the stations within the catchments. Streamflow data was available for all catchments for the period 01/01/1973-31/12/1981, thus a confirmation exercise where simulated streamflows were compared to observed flows was undertaken for this period. The statistics of performance comparing observed and simulated streamflows are given in Table 3.11. The relatively high R^2 value that was obtained, with a slope close to 1 and intercept of close to 0 indicated an adequate simulation of streamflow. Once the model configuration had been confirmed for the catchments, the ACRU model was rerun with rainfall records from the SAWS station near the hotel as this climate station has been recording continuously since 1936 to present day, and could provide rainfall data for extending the record. The statistics of performance comparing observed and simulated streamflows are given in Table 3.12. The statistics indicate a poorer simulation of the observed values using the SAWS rainfall when compared to the statistics from the simulation using the rainfall from the catchments. However, the simulation is considered acceptable.

Table 3.11: Statistics of performance of the ACRU model Cathedral Peak Catchments: Comparison of Daily Observed and Simulated Values using the catchments rainfall

Catchment (1973-1981)	III	IV	VI	VII	IX
Total observed flows (mm)	4456.079	7225.250	7537.535	5828.183	5816.046
Total simulated flows (mm)	7918.744	5001.503	4678.749	4961.746	5076.774
Ave. error in flow (mm/day)	1.053	-0.761	-0.978	-0.297	-0.225
Mean observed flows (mm/day)	1.356	2.473	2.580	1.995	1.769
Mean simulated flows (mm/day)	2.409	1.712	1.601	1.698	1.545
Std. Deviation of observed flows (mm)	2.037	3.208	2.688	2.518	1.872
Std. Deviation of simulated flows (mm)	3.122	2.410	2.345	2.393	2.145
Coefficient of Agreement	0.907	0.893	0.957	0.984	0.954
Correlation Coefficient : Pearson's R	0841	0.945	0.921	0.968	0.915
Regression Coefficient (slope)	1.288	0.710	0.803	0.920	1.048
Regression Intercept	0.663	-0.043	-0.471	-0.137	-0.310
Coefficient of Determination: R^2	0.706	0.893	0.848	0.938	0.837
Nash—Sutcliffe Efficiency Index (E_f)	0.557	0.799	0.714	0.924	0.824

Table 3.12: Statistics of performance of the ACRU model Cathedral Peak Catchments: Comparison of Daily Observed and Simulated Values using the SAWS station rainfall

Catchment (1973-1981)	III	IV	VI	VII	IX
Total observed flows (mm)	22368.45	7225.250	7537.535	5828.183	19209.76
Total simulated flows (mm)	28503.48	6554.362	6540.334	6565.385	15853.78
Ave. error in flow (mm/day)	0.436	-0.230	-0.341	0.252	-0.272
Mean observed flows (mm/day)	1.591	2.473	2.580	1.995	1.558
Mean simulated flows (mm/day)	2.027	2.243	2.238	2.247	1.286
Std. Deviation of observed flows (mm)	2.085	3.208	2.688	2.518	1.638
Std. Deviation of simulated flows (mm)	2.574	3.868	3.850	3.848	1.762
Coefficient of Agreement	0.864	0.621	0.616	0.655	0.903
Correlation Coefficient: Pearson's R	0.778	0.527	0.519	0.556	0.835
Regression Coefficient (slope)	0.961	0.636	0.744	0.849	0.898
Regression Intercept	0.498	0.671	0.320	0.553	-0.113
Coefficient of Determination: R^2	0.606	0.278	0.270	0.309	0.697

3.3 Data collection and Management

As detailed above, there is a substantial amount of historical climatological and hydrological data available for the Cathedral Peak research catchments. With the reestablishment of monitoring, the volume of data will continue to grow. With any long-term monitoring site it is essential that the data collected is of high quality. To ensure the quality of the data, set data collection procedures and protocols should be followed on each site visit. The suggested procedures and protocols for the Cathedral Peak research catchments are described below.

3.3.1 Data collection procedures and protocols

The importance of hydrological data has long since been realized internationally by numerous organizations and authors (Carrera *et al.*, 1984; Gburek, 1998; Ritter and Shirmohammadi, 2000; Mulla, 2003; Terakawa, 2003; Brooks *et al.*, 2012). For there to be useful hydrological data for the Cathedral Peak catchment into the future, it is necessary to establish a long-term strategy towards a hydrological monitoring network for the Cathedral Peak catchments. This strategy is underpinned by collection procedures and protocols in order to maintain raw data quality, and to govern the data processing and error checking procedures. The aim of establishing a standard procedure and protocol is to provide stationarity to time series data. This is particularly critical to the Cathedral Peak catchments that have been identified for the assessment of climate change over time.

Data download procedures for the various different types of equipment, established currently in the Cathedral Peak research catchment, are described below. In addition, raw data storage, data processing and recommended error checking protocols, performed once back in the office, are also described. A good quality field laptop with a battery in good condition is required to download and check the data (sometimes while in the field).

3.3.2.1 Site Access and Data Collection

Automatic weather station

There are two automatic weather stations in the Cathedral Peak research catchments. They are both Campbell Scientific weather stations and information regarding the weather stations is provided below. A third automatic weather station is located at the base of Mike's Pass near the Ezemvelo KZN Wildlife offices and is a Davis weather station. Details of this are not included in this report as it falls outside the research catchments.

One of the Campbell Scientific stations is located at the top of Mike's Pass. The station was installed in August 2012 at the same location where a weather station was previously operational until 1994. Measurements are performed every 10 seconds, and 5 minute, hourly and daily outputs are stored on a datalogger (CR1000, Campbell Scientific Inc., Logan, Utah, USA). The internal Lithium battery TL-5902S (3.6 V) should be routinely changed every three years and the desiccant inside the datalogger panel should be changed as well. Desiccant in the enclosure should be changed every three months and the enclosure should be kept well sealed to prevent the exchange of humid air.

The following information describes access to the site and the data download procedure that should be followed:

1. The weather station (-28.9755 S, 29.2359 E) is located in a fenced area that is locked. The key is currently available on the SAEON Cathedral Peak key set. This key provides access to this fenced area and opens the datalogger enclosure at the station (Figure 3.6).
2. Once the logger box is open you will be able to see the battery. Use a multimeter to measure the battery voltage and make a note of this in a field book. On the datalogger (Figure 3.7) there is a port labelled RS232. The modem for the logger is connected to this port, using the screw driver that is located in the logger box, disconnect the modem and connect the download cable to the RS232 port. Connect the download cable to the PC and open the Loggernet software. Under the main menu in Loggernet (Figure 3.8), select "connect" (Figure 3.9), then choose the 'Mikes Pass' connection option on the left side panel and select "connect" (top left of the window). See Appendix D for specifications of the CR1000 datalogger and Appendix E for details of the program running on the CR1000 datalogger.
3. Once connected successfully (indicated by the two plugs on the bottom left of the connect screen coming together), check that the station time and server time are close (within 20 s) of each other. If the station time (datalogger time) is not accurate, select 'set' to reset the time. Note the adjustment in the field notebook so that the timestamp of historic data can be corrected.
4. Choose the tab that is labelled "custom download". Under the custom download window make sure the options to "append to end of file" and "download data since last collection" are selected. Then chose the tab to "start download". The files should already be set up correctly and the data will start to download, appending to the files already on the laptop if used previously to download. Once the data has finished downloading a window will pop up showing the data files downloaded and should include the daily, hourly and 5 min recording interval files.

Figure 3.6: Installation of the automatic weather station at Mikes Pass in August 2012

Figure 3.7: Datalogger at the Mike's Pass automatic weather station

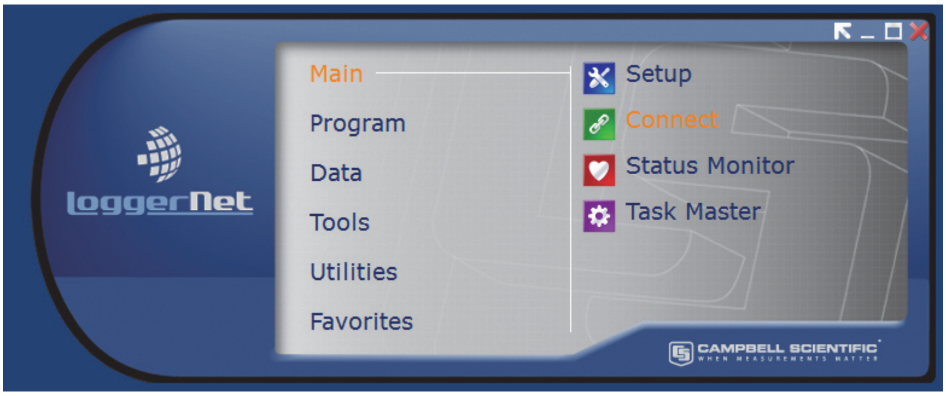

Figure 3.8: The main Loggernet software interface

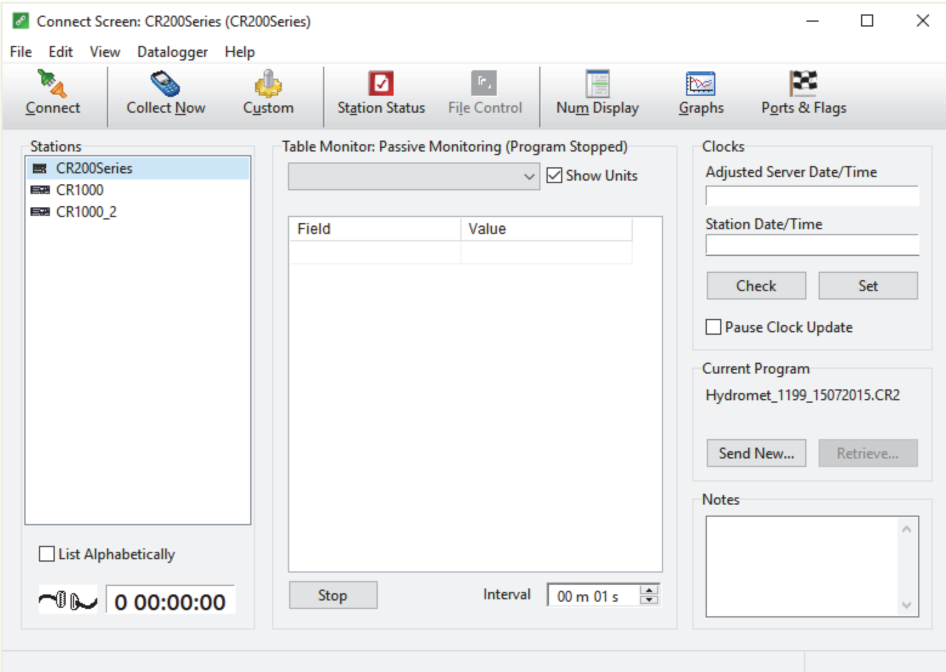

Figure 3.9: The Loggernet 'Connect' screen

5. In the pop up view window, select a downloaded data file to view and check the following:
   a. Scroll to the end of the file and see that the last data point is for the date and time at which you have just downloaded.
   b. Plot each of the variables measured by using the graph option in the view window and check that the data is realistic and that the battery voltage remain > 12 V through the measurement period. It is charged by a 20 W solar panel and should charge to 13.8 V during cloudless days.
6. The data files can be viewed at any time by going to Loggernet and selecting ‘Data’ and ‘View Pro’. The data files are in ASCII format and can be imported into Microsoft Excel.
7. If all the data is realistic, close the viewing and download windows, select disconnect and then close Loggernet. Remove all download cables and replace the modem cable to the RS232 port. If the data is not correct, make a note of what seems to be the problem and immediately notify the technician in charge of maintaining the system.
8. It is important to note that if a new program is installed on the datalogger, the following needs to take place:

   a. A complete download of the data and a retrieval of the existing program on the logger to be saved under the logger program file with the date it was downloaded.
   b. The new program is then to be uploaded to the logger. If there are changes to the output tables, all the data that is on the datalogger will be erased.
   c. If the new program has different table definitions you will not be able to download the data to the old file by appending to the end of the file.
   d. A new file will have to be started that contains the same file name but is saved under a different folder name in the location of the data downloads. The file name should consist of the date and if possible a bit of description as to why it was changed.
9. Perform a visual inspection of the sensor wires and sensors. The following sensors are located at the site and should be serviced in the following way:
   a. The net radiometer (NRLite, Kipp and Zonen, Delft, The Netherlands) should be cleaned with a soft brush and water. Note that this measurement has a dynamic wind speed correction performed in the program.
   b. The wind sentry (Model 03002, R. M. Young, Traverse city, Michigan, USA) bearings should be checked. The movement of the cups and vane should not be inhibited by the bearings running rough. Note that a wind speed of < 0.21 m s-1 is floored. Point the wind direction sensor in a known direction and confirm that the wind direction measurements of the public table are accurate. Adjust accordingly if inaccurate.
   c. The air temperature and relative humidity sensor (CS215, Campbell Scientific Inc., Logan, Utah, USA) should be securely fixed inside a 6-plate radiation shield. The radiation shield should be brushed clean with water (after removing the sensor). The filter in the cap of the sensor should be replaced when required, or at minimum every 4 years.
   d. The sieve and orifice of the raingauge (TE525, Texas Electronics Inc., Dallas, Texas, USA) should be clear of debris and seeds that may cause blockage. The top of the raingauge should be removed so that the inside of the raingauge can be cleaned with water and a soft brush. A note should be made in the field book if the tipping bucked is tipped and this data should be floored.
   e. The fog gauge should be visually checked for damage. The connection of the hoses from the funnels and into the raingauge should be checked for leaks.

The second Campbell Scientific station is located on the escarpment (Figures 3.10 and 3.11) and is accessed using a helicopter. Westline Aviation Drakensberg (**www.berghelicopter.co.za**), should be contacted for support in this regards. The instrumentation is similar to that at the top of Mike's Pass (Figure 3.6). Telemetry is enabled on this station using a GPRS modem that connects to the CSAfrica server and the ASCII data is downloaded to the SAEON office.

Figure 3.10: Campbell Scientific automatic weather station on the Drakensberg escarpment. A normal raingauge (in the background) and a fog-gauge (foreground) have been installed to monitor precipitation

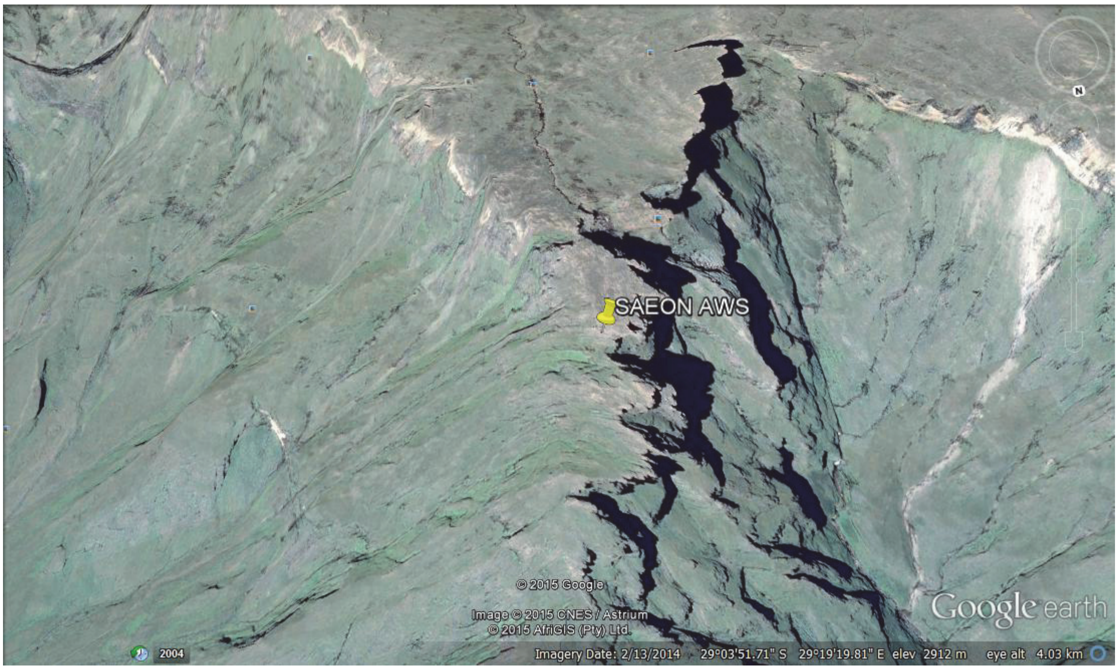

Figure 3.11: Location of the high altitude automatic weather station

Raingauges

Raingauges are distributed across the research catchments without fences or enclosures around the sites (Figure 3.1). Two types of tipping bucket raingauges have been installed in the catchments. In catchments I to III and catchments VIII to XII, Davis-MC Systems (D-MCS) raingauges (Figure 3.12) were installed. These D-MCS raingauges were calibrated and each raingauge has a multiplier (Table

3.13). The D-MCS raingauges can become blocked with grass seeds. The original sieves provided with the raingauges were blown out of the orifice in high winds. They have therefore been modified with a mesh glued into the orifice to prevent blockages. The orifice should be kept as clean as possible for accurate data collection.

Texas Electronics (TE525) high intensity raingauges (Figure 3.13) were installed in catchments IV to VII and have multipliers of 0.254 mm per tip. The Texas raingauges have built-in sieves that catch objects that could cause blockage and should be cleaned regularly. All raingauges should be calibrated on an annual basis.

Data from both raingauge types are recorded on an Onset HOBO Pendant Event Datalogger (UA-003-64) recording break-point data and accumulating tips. The Hobo pendants (Figure 3.13) are powered by a CR2032 battery that should last a year depending on rainfall. This battery voltage can be viewed using a laptop running the Hoboware software (described below) when connected to the Hobo pendant. The batteries should however be routinely changed every 9 months to avoid data loss and the desiccant pack should also be replaced at the same time. The pendants are located inside the raingauges and can be accessed by removing the raingauge covers.

The following section describes downloading rainfall data:

1. Note the GPS locations for all the remote rainfall sites if unfamiliar with the catchment and use a GPS to locate the raingauges (Table 3.13).
2. The data should be downloaded using the Hobo U-Shuttle and a connection cable.
3. Remove the raingauge cover and remove the pendant datalogger. Plug the connection cable into the shuttle and then insert the pendant logger into the other end of the cable so that the infra-red sensor (same side as flashing light) faces a corresponding sensor in the connection cable.
4. When the shuttle is turned on using the “esc” button you will get two options. The first is to find the a device by pressing the “yes” key and the other will give you info about the shuttle by pressing the “no” key. Press yes to find the device.
5. It will search for the pendant and then display the battery and memory usage of the pendant. If this does not display, the pendant is not connected to the shuttle properly. If it repeatedly does not read, remove all cables and restart the shuttle. Press the “yes” key to continue downloading. Low batteries should be replaced with a CR2032 battery. It will ask if you want to view the real time sensor outputs. Press no unless you want to see the current values for the temperature sensor.
6. Proceed to readout the logger. This will download the data from the logger to the shuttle. Press yes to download the data.
7. When the offload is complete and you are given the option to restart the pendant. Restarting will remove all the data on the pendant and start recording again. Select no to keep the data on the pendant and continue recording from the last data point. It is best to restart the logger when the memory on the logger is around 50% (will be displayed on start-up) to prevent data loss due to the memory becoming full.
8. To retrieve the data off the shuttle, connect the shuttle to the computer using its computer connection cable and open the Hoboware software.
9. In one of the drop down menus (Device), select the option to manage shuttle.

10. In the dialog box that opens select all the files that are displayed on the shuttle and choose the option to offload the files.
11. Once the files have been offloaded choose the option to save all the files again and then sync the clock and re-launch the shuttle.
12. The files downloaded are in a binary format native only to Hoboware and should be exported to ASCII so that they can be opened in Microsoft Excel.

Figure 3.12: Laboratory calibration of a Davis raingauge with (a) cover and (b) without cover

Figure 3.13: (a) Texas Electronics high intensity raingauge; (b) Onset Hobo Pendant

Table 3.13: Summary of automatic raingauge locations in the Cathedral Peak catchments with multiplier given for Davis type gauges

Raingauge	Latitude	Longitude	Altitude	Aspect	Slope	Type	Multiplier
Mikes Pass	-28.9546	29.2372	1556	58.39	13.88	Texas	0.254 mm
Office Station	-28.9755	29.2359	1861	7.59	2.34	Texas	0.254 mm
IC	-28.9814	29.2376	1846	31.61	4.71	Davis	0.2 mm
IIA	-29.0049	29.2208	2292	6.19	34.54	Davis	0.2 mm
IIB	-28.9967	29.2226	1974	47.73	9.12	Davis	0.2 mm
IIC	-28.9911	29.2271	1867	331.62	7.60	Davis	0.2 mm
IIIA	-29.0047	29.2306	2197	45.00	4.91	Davis	0.2 mm
IIIB	-28.9961	29.2337	1973	91.88	9.35	Davis	0.2 mm
IVA	-29.0035	29.2396	2134	1.71	22.12	Texas	0.254 mm
IVB	-28.9985	29.2413	1949	357.56	7.24	Texas	0.254 mm
IVC	-28.9910	29.2439	1852	340.46	5.07	Texas	0.254 mm
VA	-28.9980	29.2482	2068	340.60	5.80	Texas	0.254 mm
VIB	-28.9931	29.2518	1923	351.38	10.21	Texas	0.254 mm
VIIA	-28.9931	29.2566	1986	343.33	12.47	Texas	0.254 mm
VIIB	-28.9901	29.2568	1910	320.65	9.90	Texas	0.254 mm
VIIC	-28.9879	29.2523	1849	291.04	6.43	Texas	0.254 mm
VIIIA	-28.9829	29.2620	1919	150.52	2.04	Davis	0.2 mm
VIIIC	-28.9844	29.2679	1883	100.71	2.91	Davis	0.2 mm
IXA	-28.9912	29.2629	1969	57.47	11.49	Davis	0.2 mm
IXB	-28.9909	29.2662	1903	79.19	6.97	Davis	0.2 mm
IXC	-28.9921	29.2734	1828	118.30	2.28	Davis	0.2 mm
XA	-28.9973	29.2539	2009	125.12	16.71	Davis	0.2 mm
XC	-28.9981	29.2629	1848	99.61	5.08	Davis	0.2 mm

Streamflow

During 2012 and 2013 the weirs at catchment outlets IV to VII were cleaned out and some minor repairs to the structures and stilling wells were undertaken. Measurement of the water stage-height (Orpheus Mini, Ott Hydromet GmbH, Germany) at catchments IV to VII has been implemented (Figure 3.14a) using half hourly monitoring. The Orpheus Mini is a vented pressure transducer and does not require corrections for atmospheric pressure. Battery levels should be monitored from the OTT Orpheus Mini software when connected using a laptop and replaced with LR6/FR6 AA batteries when the voltage is less than half (Figure 3.14b). In addition, the desiccant in the communication unit should be changed every three months (Figure 3.14c).

The following data download procedure should be followed at the weirs:

1. If there is debris in the v-notch, record stage height measurement of the water level before removing the debris from the weir;
2. Remove debris from V-notch before commencing the data download as this will allow time for the weir to reach and equilibrium before the v-notch level is recorded;
3. Once the V-notch has been checked and cleared of debris, remove the Ott logger cap with the specialized key and open the cap;
4. With the cap open:
    a. Turn on a field laptop;

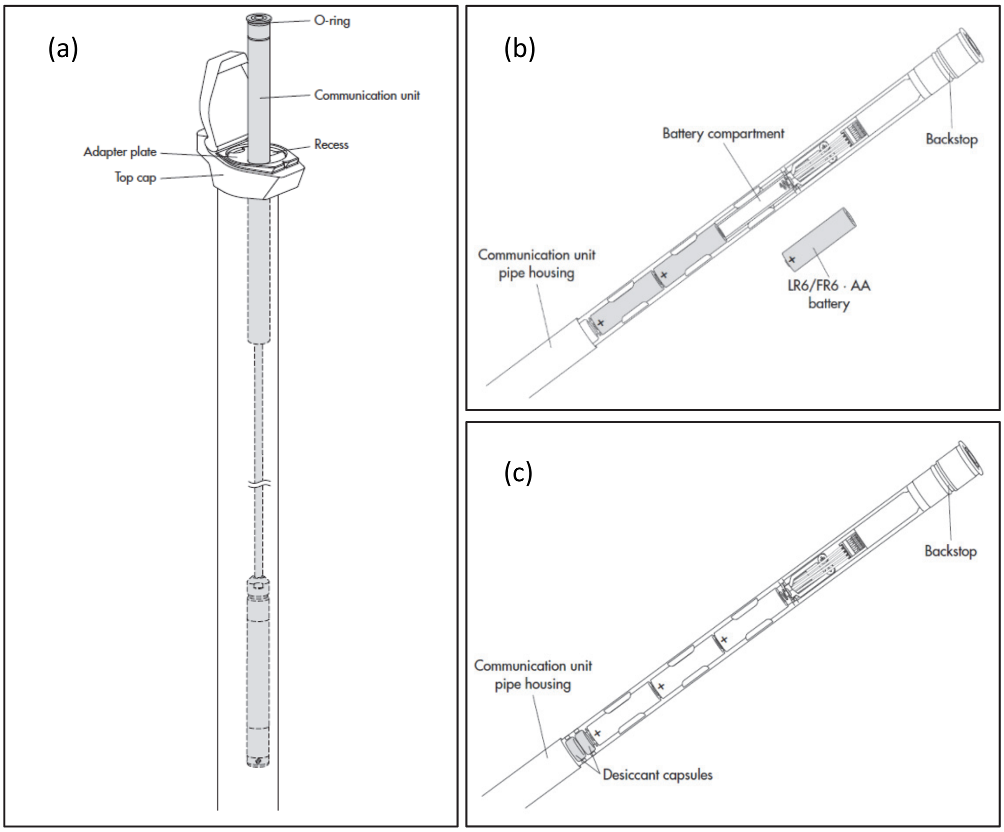

Figure 3.14: (a) Orpheus Mini water stage height recorder shown in grey; changing the Orpheus Mini (b) batteries and (c) desiccant

   a. Attach connection cable to Orpheus Mini and laptop;
   b. Open OTT Orpheus Mini software;

5. Select the option to "Download Data";
6. Make sure that your connection settings are set to "IrDA - OTT DuoLink" with the correct com port selected and choose the "Connect" button;
7. Select the option to download data tables 0001, 0002 and 0003 from the datalogger. The download process can take some time depending on the length of data record to be downloaded. Once the data is downloaded, choose the option to view exported data either from the download window or by going back to the main screen and selecting "View / Export Data";
8. To check/view the streamflow data, select output 0001 from the station just downloaded and the 0002 output for temperature. The 0003 output is a raw data file and is not relevant for checking;
9. Once all the data has been checked and any problems corrected, the OTT software can be closed, the connection cables removed and the logger cap re-secured.
10. Using a staff gauge, measure the height of the water flow over the V-notch of the weir and record in a field notebook. A difference in the measured stage height from the sensor and that from the staff gauge should be investigated. Any movement or change in position of the pressure transducer in the water can alter the measurements as well as sediment build-up over the sensor. The sensor should therefore be cleaned monthly with soft brush to remove

sediment and algae. The area around the pressure transducer in the stilling well should also be kept free of sediment especially during summer when deposition is likely to be highest.

11. During winter each year, deposition in the weirs should be evaluated and they may require cleaning. Notes on sediment depth removed should be recorded.

Specialised equipment

There are currently two specialized systems deployed in Catchment VI. These include an Open Path Eddy Covariance system and Cosmic Ray Probe. The Eddy Covariance system provides data on energy fluxes and allows for the measurement of total evaporation, carbon flux and the surface energy balance. The Cosmic Ray Probe provides a measure of the average catchment volumetric water content of the soil. Further details of the Eddy Covariance system can be found at www.campbellsci.com and the Cosmic Ray Probe at http://hydroinnova.com.

3.3.1.2 Protection of equipment and personal safety

Grass fires are common in the Cathedral Peak catchments and occur most frequently in the winter months between May and October. Fire damages the cables, batteries and equipment in the field and precautions to avoid fire damage should be taken each year. Fire-breaks should be burned around sites or the equipment should be removed during a planned burn. Ezemvelo KNZ Wildlife manages the burning in the catchments and should be contacted to make arrangements before the winter season arrives. Fire also poses a threat to humans and vehicles and the catchments should be vacated if there is any sign of fire.

Theft of equipment has been a problem in the Cathedral Peak catchment in 2014 and 2015. Batteries and solar panels are the most sought after items although metal poles and dataloggers have been stolen as well. It is necessary to secure batteries in strongboxes that are concreted into the ground and to avoid the use of solar panels where possible as they are highly visible and attract attention.

A reliable weather forecast should be accessed before entering the catchment. Mike's Pass is closed in wet conditions. Adverse weather can occur in the Cathedral Peak catchments at any time of year and includes violent storms, high wind speeds and snow falls. Suitable warm clothing should be carried as well as a hat and suntan lotion.

Do not leave cars open or food out in the open as this can attract baboons. In addition, snakes occur in the grassland and visitors to the catchments should be familiar with treatment of snakebites and know how to respond. Never work alone in the catchments.

The incidence of lighting in the Cathedral Peak area during summer is high (Gijben, 2012). During lightning storms, avoid peaks and ridges and other high-lying areas. The safest place during a lightning storm is in a vehicle. Alternatively, if there is no vehicle nearby, assume a lightning crouch position, in low-lying landscape, with feet together and hands off the ground (Figure 3.15). Use a clickboard, blanket or any other insulation to minimize contact between your feet and the ground.

People should wait out the storm in this position with a distance of approximately 50 m from each other.

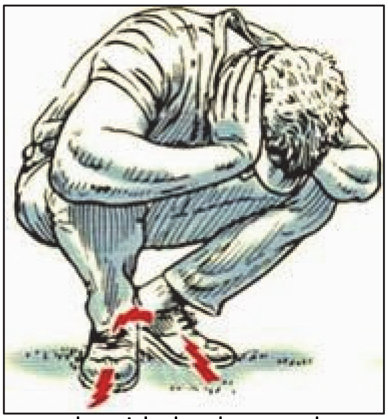

Figure 3.15: The lightning crouch with heels together minimizes the risk of a ground-surge travelling through the body (Lucas, 2015)

3.3.1.3 Data Management

There may be times when data is downloaded and a datalogger is relaunched and the memory of the datalogger is erased. Under these circumstances, the only copy of the data is on the field laptop until it is backed up. It is therefore imperative that the data be copied from the field laptop (or storage device such as a shuttle) to a network drive (that is backed up regularly). This should be performed immediate on returning from the field. If staying a number of days in the field, backup the files onto a memory stick every evening in case of accidental damage to the laptop or storage device.

On a network drive, a logical directory and file structure is required for backup files and user permission should be controlled with select users having full access and others provided with 'read only' access. The directories and files should be labelled according to the type of measurement made and the data of download. For example, 'Rainfall', Streamflow' and 'Weather' are suitable directory names. Save the raw data files (binary format) as well as the exported ASCII files onto the network drive using the date and type of measurements in the name. For example data download from the weather station on 19 March 2015 could be labelled '20150319weather station'. If the naming convention is YYYYMMDD then the files will order correctly in Windows Explorer when sorted according to name.

In addition, photos of the sites can be very useful references in the future and there should be a folder specifically for photos. They should be saved in a folder named according to the YYYYMMDD on which they were downloaded. The date on which they were taken is usually stored in the properties of the image. Notes on their location and any extra information on the photos should be saved in a Text or Microsoft Word file in the directory with the photos for reference in the future. Some cameras are able to store the location (GPS coordinates) where the photos were taken.

The final storage destination of the time-series data from the Cathedral Peak research catchment will be the SAEON data portal. Each site will may have different data files associated with it. For example raw binary files and exported ASCII files should both be stored in the data portal but with the relevant metadata attached. Notes from the fieldbook should be converted to electronic format and uploaded onto the system indicating battery voltages, damage, urgent maintenance and any additional observations made that may be useful in the future for interpreting the data. Notes on the evidence of snow, high wind speeds, fires etc. should be recorded.

Before uploading the data onto the SAEON data portal it is necessary to verify the data integrity downloaded in the field. Visual inspection of the data in a graph as well as confirmation of the continuity of the data since the last download is necessary. If data is missing, it should be noted as the data may still be on a datalogger in the field and can be downloaded. The raw data files can be viewed in their native software. For example, the rainfall files can be viewed in Hoboware or the exported file can be opened in Excel and graphs created. The weather station data can be viewed in Loggernet View Pro or Microsoft Excel. Outliers should be noted and flagged if possibly erroneous. Use related data to confirm possible errors and outliers. Streamflow outliers for example, can be verified by plotting a time-series graph of streamflow and rainfall. Peaks in the streamflow should correspond with rainfall events from some of the raingauges across the catchment. Software to identify data that is out of range as well as invalid data readings should be used to filter out problems. Different dataloggers have their own conventions to indicate data problems. Campbell Scientific loggers will output a “NAN” which stands for “Not a Number”. Other dataloggers may record “-9999”. The data files should all be processed through filtering software to identify any of these records so that they can be evaluated for patching.

Patching missing data may be required and should be conducted only where valid. Missing rainfall records for example can be patched where good relationships exist between neighbouring raingauges. This relationship may however vary with the type of rainfall (convection or frontal) occurring. See Section 3.2 on the approach used for patching rainfall records during the course of this study.

One of the key aspects to ensure the optimum use of the data to advance hydrological understanding will be the appropriate storage of the data in an accessible location and more importantly the record of the meta data associated with it. Both the historical and current data from the Cathedral Peak research catchments, together with the meta data, will be stored and made available through the SAEON data portal as detailed in the section which follows.

3.3.2 Description of SAEON Data Portal

SAEON is committed to making data available to the research community to enable Global Change research. This is facilitated through the SAEON data Portal. Initial versions of the portal environment were used to test its value and develop specifications for a refined upgraded portal environment that caters for the needs of scientists for uploading data as well as searching for data. Initially this system was designed primarily for search and discovery of meta data records. It has now evolved to house actual data to which scientists can contribute, search, visualise, explore and download. A significantly revised and more user friendly interface of the SAEON data portal will be released in 2016.

The SAEON data portal houses a diversity of data types, each supported by a background system or database. A database system was specifically developed for the purpose of housing historical and current observations of streamflow and climatic data. This system is known as the Observations Database. It is currently being expanded to cater for all types of sensor data including soil moisture, carbon flux, oceanographic measurements and web sensor data. The use of the database for this project has allowed for the testing of the system. A number of improvements to the user interface and functionality of the system consequently have been identified and actioned. Once the development improvements have been completed, the database will be visible and searchable online with all the data from this WRC project available in the open access component of the database. Components of this system include:

1. A Data Acquisition/ Import Module
2. A Database (IOM Database)
3. Administrative Data Query and Editing/ Annotation Module
4. Services: Based on REST and Sensor Observation Services API for data and meta-data.
5. A Query User Interface
6. Data visualisation, Download, and Citation module

Figure 3.16 provides a conceptual diagram of the architecture of the final system.

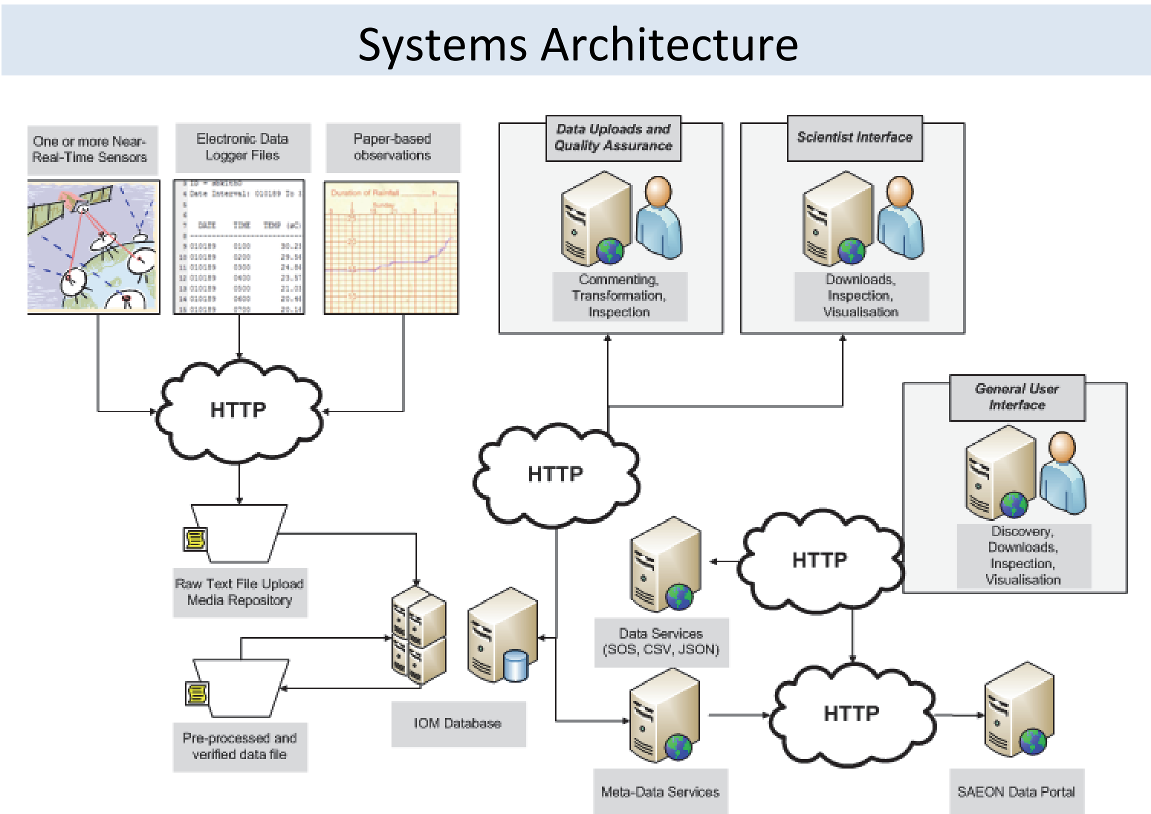

Figure 3.16: Conceptual architecture of the SAEON Observation database (From G373.7.1 User Requirements SAEON Observation database, 2015)

The data received from the CSIR is provided 'as-is' with no guarantee as to its quality or recommendation about its potential for analysis. While this historical data for the Cathedral Peak catchments will be available through the database, a key contribution from this project is revised datasets that have been error checked and infilled where possible. These will also be made available through the Observation database as a ready product for people to use for future analysis.

When uploading data to the repository there are strict requirements on the meta data required which adhere to international standards. This is highly valuable for anyone searching for data and once found is useful when accessing the data, as it details where, how and using what equipment the data was obtained and any additional information users of the data may need. Methods used for infilling of the revised databases will be captured within these meta data records.

3.4 Linking past and present rainfall measurements: A cross-calibration study

To determine changes in the climate and subsequent impacts as well as to improve process understanding, 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 changes 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. For example, it is often necessary to upgrade the equipment in order to get a better measurement or a better resolution measurement (Bartokova *et al.*, 2014). With the re-establishment of the Cathedral Peak research catchments, modern Davis tipping bucket and Texas High intensity raingauges were installed to replace the historical Snowdon raingauges.

The modern and historical raingauges have several differences that result in varying measurements of rainfall at a location. The common consensus is that the tipping-bucket raingauge underestimates the actual rainfall occurring (Colli *et al.*, 2014), due to the limitations in the tipping-bucket mechanism. While the historical Snowdon raingauges are considered to provide a good representation of the actual rainfall, due to their large funnel and accurately constructed rim (Burt, 2013). Between these raingauges there are several fundamental differences. The Snowdon gauges installed in the catchments had Nipher shields for wind protection, were placed with their orifices parallel to the slope and rain was collected in the gauge and read by pouring into a measuring cylinder at a daily, weekly or monthly frequency. The modern raingauges are installed parallel to the horizon, they do not have shields and the rainfall is measured by a count of the number of bucket tips. Thus it is necessary to develop a relationship between the rainfalls measured by these two different gauges to allow for the rainfall records from the two different gauge types to be compatible. In addition to this, the rainfall distribution and characteristics across an area vary depending on the slope and aspect of the sites (Buytaert *et al.*, 2006). As a result, each raingauge site throughout a mountainous area will have a different rainfall reading, even over a small area (Buytaert *et al.*, 2006). Therefore, as stated by Essery and Wilcock (1991) and Mekonnen *et al.* (2014), there is a need to develop site specific correction factors. Thus to ensure the compatibility of the historical and current rainfall records in the Cathedral Peak research catchments, a cross-calibration of the modern and the historical raingauges was conducted. In addition, the question of the accuracy of the Snowden and modern raingauge was addressed through comparison against a ground level gauge, which the WMO considers to be most accurate. The influence of the Nipher shield was also investigated.

3.4.1 Methodology: Site selection, raingauge design and error checking

For this cross-calibration study, 12 raingauge sites where modern gauges have been installed were chosen from the 26 historical raingauge sites. 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. The details of the 12 selected sites are shown in Table 3.14 with their respective locations shown in Figure 3.17.

Table 3.14: The characteristics of the raingauge sites selected for the research at Cathedral Peak

Raingauge Site	Latitude	Longitude	Altitude (m.a.s.l)	Aspect	Slope Angle (^{o})
Mike's Pass station	-28,976	29,236	1866	North	0,00
IIB	-28,997	29,223	1975	North East	13,85
IIC	-28,991	29,227	1875	North West	21,52
IIIB	-28,996	29,234	1969	East	13,54
IVA	-29,004	29,240	2144	North East	41,42
IVB	-28,998	29,241	1960	North	12,68
VA	-28,998	29,248	2068	North	16,23
VIIA	-28,993	29,257	1976	North West	24,96
VIIC	-28,988	29,252	1849	West	11,26
VIIIA	-28,983	29,262	1920	South East	12,81
IXA	-28,991	29,263	1968	East	22,17
XA	-28,997	29,254	2021	South East	24,75

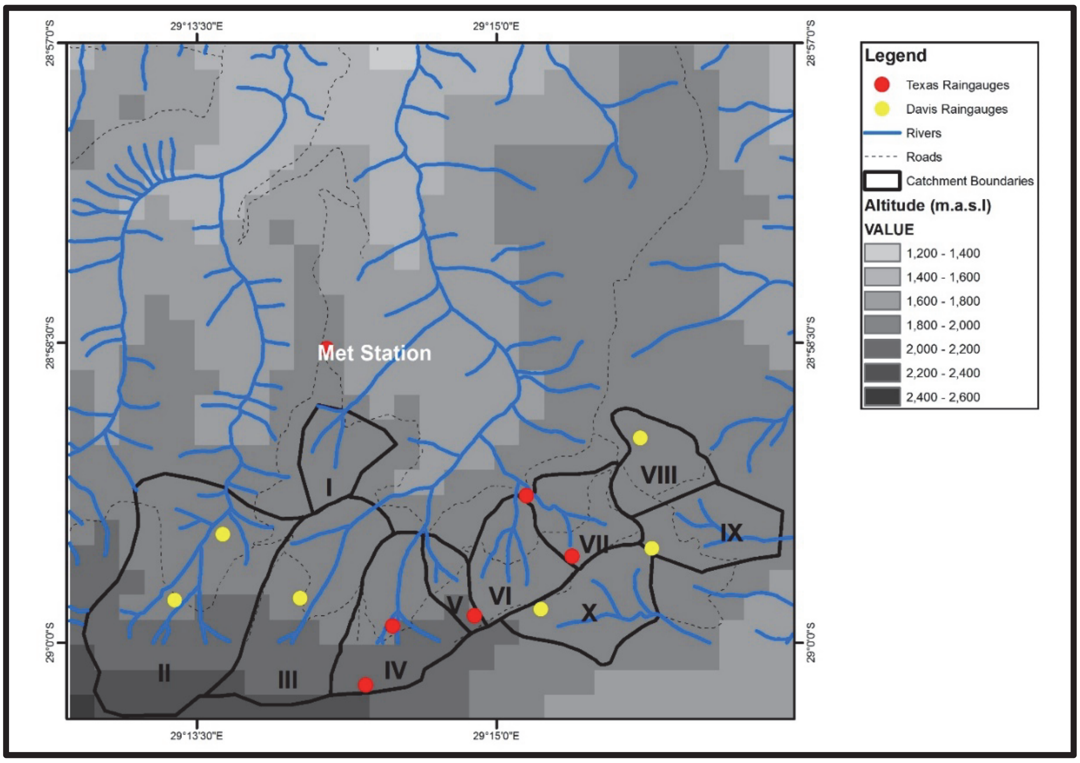

Figure 3.17: Location of the raingauges sites where the cross-calibration was undertaken, with the Texas high-intensity (Red) and Davis tipping-bucket (Yellow) raingauges shown

Raingauge design and measurement

The historical raingauges used in the Cathedral Peak research catchments were Snowdon raingauges. For the cross-calibration, a Snowdon replica raingauge as shown in Figure 3.18 was made and placed into the remaining Nipher shields in the catchments. The Snowdon raingauges are parallel to the catchment slope. The manual Snowdon raingauges are measured on a monthly basis during site visits, using a measuring cylinder. Each month after the recording, a single drop of paraffin is added to the storage container to prevent loss due to evaporation. The automatic raingauges continuously record rainfall as it occurs and the data is downloaded during the site visits. The groundlevel raingauge and Texas high-intensity raingauge within a Nipher shield were installed at the Mike's Pass meteorological station to address the additional research questions of the accuracy of the gauges and the influence of the Nipher shield.

Figure 3.18: A Snowdon raingauge with Nipher shield at the angle of the slope, with a vertically positioned Texas raingauge in the background (left). Replica of the historically used Snowdon raingauge placed within the Nipher shield (right)

Error checking and data processing

During the data collection phase, several errors occurred in the data due to raingauge storage, animals, fires, blockage and data corruption. Rainfall recording using the retrofitted historical gauges commenced at the start of February 2014. The rainfall for February 2014 was greater than expected for the catchments based on historical records. As a result, several of the historical Snowdon raingauges overtopped before they could be recorded (Figure 3.19) resulting in the historical raingauges recording much lower rainfall values than the modern raingauges, and similar amounts across all gauges. Additionally, the storage container of the historical gauge at VIIC leaked, thus no rainfall was recorded at this site. A further error identified was the low rainfall recorded by the modern gauge at site IVA (Figure 3.19) due to the gauge being blocked. This continued to be problematic through the study, thus this site was excluded from the analysis. These values have been removed from further analysis. To identify further errors all the rainfall data for Cathedral Peak was plotted with the modern and historical raingauges on the x and y axis, respectively (Figure 3.20).

For example, where one gauge type recorded substantial rainfall and the other type at the same site recorded no rainfall, those values were interrogated and removed where necessary.

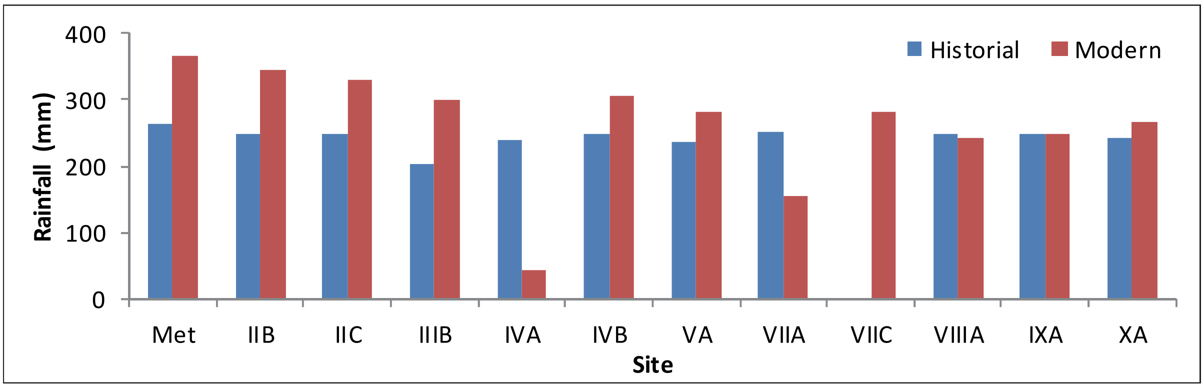

Figure 3.19: Rainfall recorded for February 2014 by the historical and modern raingauges

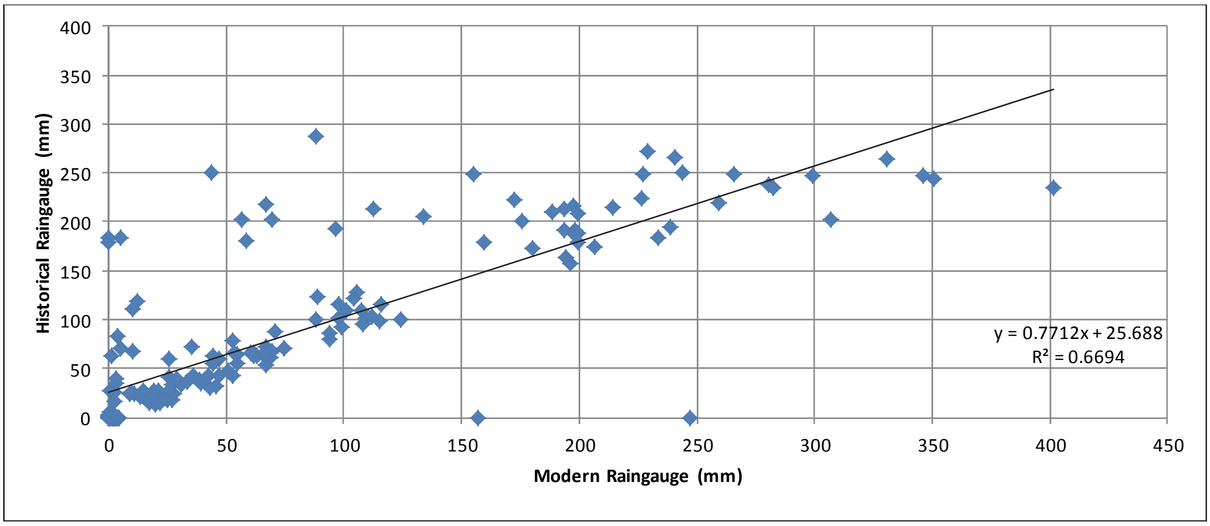

Figure 3.20: A comparison of the historical and modern raingauges using the complete set of data recorded at Cathedral Peak

3.4.2 Results: Relationship between the Modern and Historical Raingauges

The corrected data recorded over the 16 month period at Cathedral Peak for the modern raingauge plotted against the historical raingauge records is shown in Figure 3.21. The difference between the rainfall recorded by the historical and modern raingauges are small, with the Snowdon raingauge recording slightly more rainfall for larger rainfall events. The period of data recording covered two wet seasons and one and a half dry seasons. In order to understand the relationship between the raingauges, the influence of seasonality needs to be considered.

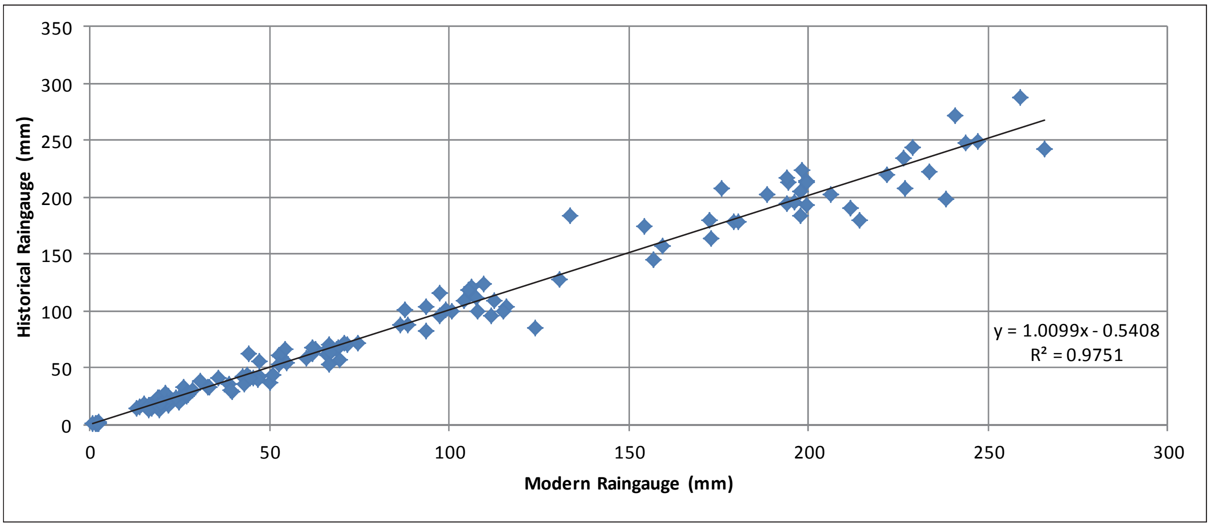

Figure 3.21: Comparison of corrected rainfall recorded using a modern and historical raingauge for Cathedral Peak

Cathedral Peak receives the majority of its rainfall in summer with low rainfall during winter, and the rainfall has a high inter-annual variability. For example, the April rainfall in 2014 and 2015 are considerably different (Figure 3.21). March has been used as an example to indicate the relationship between the raingauges in a relatively wet month, April a transition period into the dry period. With higher rainfall, the differences between the historical and modern raingauges appears to be greater (Figure 3.17). As the rainfall volume decreases, the difference between the raingauges tends to decrease. However, this does not hold true for every site. The difference between the raingauges may vary with rainfall volume, which can be related to seasonality, however other factors such as the tilt of the historical raingauges, the aspect of the sites and the altitude of the sites could have an influence on differences between the modern and historical raingauges.

To determine whether slope, aspect and altitude of the raingauges site has an influence on the difference between the modern and historical raingauges, percentage differences between the modern and historical raingauges were calculated relative to the modern raingauges for the Cathedral Peak sites, these are shown in Table 3.15. The sites have been ranked in order of their differences between the modern and historical raingauges.

For sites with a steep slope (>20^{o}) the modern raingauge appears to record more rainfall than the historical raingauge regardless of the modern raingauge type (Table 3.15). This may be due to the tilt of the historical raingauge which becomes a significant influence when the site is sloped at more than 20^{o}. For sites where the slope is not significant (<10^{o}), such as VIIC and the Mike's Pass meteorological station the difference between the historical and modern raingauges is minor (Table 3.15). For sites with slopes between these ranges, four sites indicate that the modern raingauge records less than the historical gauge, one site shows the modern gauge to record more, and the last site shows an insignificant difference (Table 3.15).

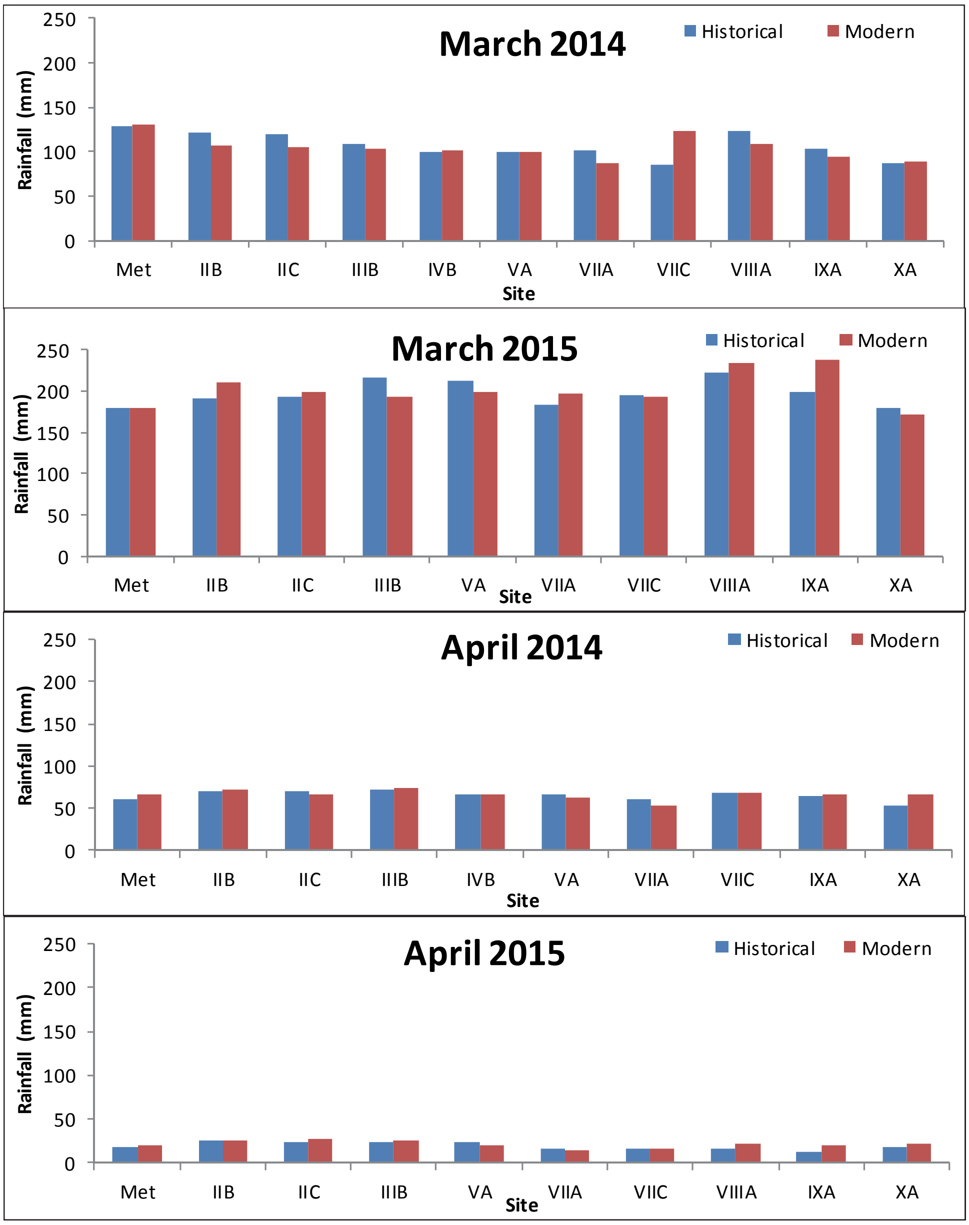

Figure 3.22: Rainfall recorded by the historical and modern raingauges for March 2014 and 2015, and April 2014 and 2015 at Cathedral Peak sites

Literature suggests that altitude has an impact on rainfall volumes over a landscape. As the differences between the modern and historical raingauges tend to vary with rainfall volumes, altitude was considered as an influencing factor in the differences between gauges. No influence of altitude on the difference between the modern and historical raingauges, however, was evident (Table 3.15). At the highest site (2063 m), the modern raingauge recorded 8.9% less rainfall, while at the second highest site (2030 m) the modern raingauge recorded 5.8% more rainfall. There is no clear pattern in the differences between the modern and historical raingauges at Cathedral Peak which can be attributed to altitude at this time. Likewise, no relationship between aspect and the differences between the raingauges is evident (Table 3.15). The two East facing sites show large differences between the modern and historical raingauges, however the direction of the difference varies with the modern raingauge at site IXA recording 7.4% more rainfall, while at site IIIB the modern raingauge records 8.8% less rainfall. Historical raingauges tend to record more rainfall at the

North facing sites (Table 3.15). Whether this is attributable to the North aspect is uncertain as sites with North East and North West aspects show no consistent pattern. As no pattern was evident in the differences between the historical and modern raingauges, the influence of the make of tipping bucket raingauge was questioned. However, no pattern for the influence of the make of tipping bucket raingauge was evident (Table 3.15).

Table 3.15: The percentage difference between modern and historical raingauges relative to the modern raingauge for Cathedral Peak sites with altitude, slope, aspect and modern raingauge type provided

Site	Difference (%)	Altitude (m.a.s.l)	Aspect	Slope (^{o})	Raingauge Type
IXA	7.4	1971	East	22.17	Davis
XA	5.8	2030	South East	24.75	Davis
IIB	5.4	1988	North East	13.85	Davis
VIIA	3.4	1984	North West	24.96	Texas
Met	0.1	1866	North	0.00	Texas
VIIIA	-0.5	1924	South East	12.81	Davis
VIIC	-1.9	1850	North West	7.49	Texas
IIC	-3.3	1884	North West	13.85	Davis
IVB	-7.3	1959	North	12.68	Texas
IIIB	-8.8	1969	East	13.54	Davis
VA	-8.9	2063	North	16.23	Texas

3.4.3 Results: Accuracy of the raingauges and influence of the shield

Through the study, the question of which gauge is more accurate arose as well as the influence of the shield vs the measuring mechanism. Thus, two additional raingauges were installed at the Mike's Pass meteorological station to address this. To address the question on accuracy, a ground level raingauge was installed. It is suggested by the World Meteorological Organisation (WMO), that a ground level raingauge can be used as a reference raingauge as it is considered to provide the most accurate measure of rainfall (Dreaver and Hutchinson, 1974; Rodda and Dixon, 2012; Mekonnen *et al.*, 2014) due to the reduced wind effects (Mekonnen *et al.*, 2014). Ground level gauges are placed in pits, with their orifices at ground level surrounded by either a mat or grid which reduces the effects of wind as well as in-splash (WMO, 2008; Mekonnen *et al.*, 2014). The influence of the Nipher shield was addressed by installing a Texas high intensity raingauge in a Nipher shield at the meteorological station. Thus allowing for the comparison between a shielded tipping bucket raingauge, a shielded Snowdon gauge, and a standard tipping bucket gauge. The installation of these two additional gauges were undertaken in January 2015, thus only data till the end of December 2015 has been included.

The percentages of rainfall recorded by each raingauge compared to the ground level gauge are given in Table 3.16 for the period February 2015 to December 2015, with April 2015 excluded due to gauge failure. The ground level raingauge consistently records the highest rainfall amounts, across both the wet and dry seasons. To answer the question of whether the Snowdon shielded gauge is more accurate than the standard tipping bucket gauge, the Snowdon shielded gauge and the Texas high intensity non-shielded gauge were compared relative to the ground level gauge.

Table 3.16: Rainfall recorded by the respective raingauges in mm and as a percentage of the rainfall recorded by the ground level gauge (S=Shielded; NS=Non-shielded) for 2015

Month	Groundlevel		Snowdon		Texas (NS)		Texas (S)	
	mm	%	mm	%	mm	%	mm	%
Feb '15	181.6	100	163.7	90.1	172.7	95.1	162.1	89.2
Mar '15	190.0	100	178.9	94.2	179.3	94.4	171.7	90.4
May '15	3.0	100	0.0	0.0	1.8	58.3	1.8	58.3
Jun '15	2.5	100	0.0	0.0	1.3	50.0	1.8	70.0
Jul '15	37.3	100	32.2	86.3	32.8	87.8	31.8	85.0
Aug '15	19.3	100	16.3	84.4	17.0	88.2	16.5	85.5
Sep '15	26.9	100	24.4	90.5	22.1	82.1	22.4	83.0
Oct '15	49.3	100	43.0	87.2	43.7	88.7	41.7	84.5
Nov '15	89.4	100	79.8	89.2	80.0	89.5	78.0	87.2
Dec '15	60.7	100	53.9	88.8	51.8	85.4	50.3	82.8
Total	660.1	100	592.1	89.7	602.5	91.3	577.9	87.5
Wet	654.6	100	592.1	90.5	599.4	91.6	574.3	87.7
Dry	5.6	100	0.0	0.0	3.0	54.5	3.6	63.6

Overall, the Texas non-shielded gauge recorded a rainfall amount closer to that which the ground level gauge recorded (Table 3.16; Figure 3.23) in comparison to the Snowden gauge. However, when the dry and wet seasons are considered separately the picture is different. During the dry months, the Snowden raingauge recorded no rainfall while the ground level and Texas non-shielded gauges recorded rainfall. This may be due to evaporation from the Snowden raingauge as it is only read once a month, while the tipping bucket gauges record the tips immediately. During the wet months, the differences between the Snowden shielded gauge and the Texas non-shielded gauge are negligible in most months and overall across the wet months (Table 3.16; Figure 3.23). The influence of the shield on the measurement of rainfall requires more analysis. At a monthly time step the Texas shielded and non-shielded raingauges generally record similar amounts to each other (Table 3.16; Figure 3.23). As these are both event based gauges, a more in-depth analysis at a finer timescale should be undertaken. What was clear from this aspect of the study, despite the short data record, was that the ground level gauge substantially more rainfall, of the magnitude of up to 13% more, than a gauge placed at the standard height of 1.2m above the ground. Furthermore, these differences were greater in the dry months.

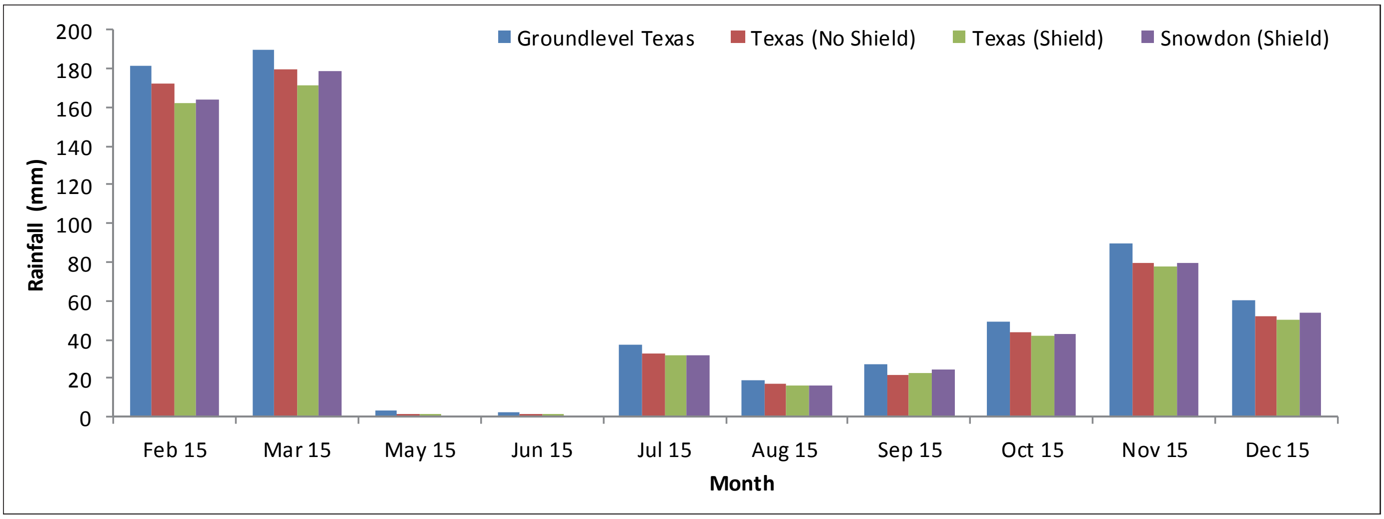

Figure 3.23: Graphical comparison of the ground level, Texas standard, Texas shielded and Snowdon shielded raingauges

3.4.4 Discussion: Differences between modern and historical raingauges

Across the Cathedral Peak sites, the historical and modern raingauges record similar rainfall volumes for the 16 months monitored, with the difference never exceeding 9%. Whether the historical raingauge records more rainfall or the modern raingauge does, varies from site to site, and from month to month. There is no consistent pattern evident. No pattern can be seen related to aspect or altitude, nor the modern gauge make. At slopes greater than 20%, modern raingauges appear to record more rainfall. This may be attributable to the tilt of historical gauges while the modern gauges are upright. Fitting a 1:1 trend line to the data, indicates that the historical raingauges record slightly more (Figure 3.21) and this is more evident at higher rainfall volumes, but this difference is less than the error of the gauges.

In order to identify whether the historical or modern raingauges are more accurate, the ground level raingauge was used as a reference gauge. The ground level gauge consistently recorded the highest rainfall totals. Based on overall totals, the historical raingauge is less accurate than the modern gauge at the Mike's Pass meteorological site as its total rainfall is less. However, if only months with more than 3 mm of rainfall are considered, then the difference between the historical and modern raingauge is only 0.6% which is insignificant given the errors associated with rainfall measurement.

The comparison between the Texas raingauge with and without a shield provided interesting results. In the dry period, when Cathedral Peak experiences low intensity, frontal rainfall, the shielded Texas raingauge records more rainfall than the non-shielded Texas raingauge. However, during the wet months, when high intensity rainfall dominates, the non-shielded Texas records more rainfall, but only by a small percentage. This may highlight the fact that the Nipher shield is influential in low intensity rainfall, but this is only based on two months of dry data. Due to this pattern arising, further analysis will take place, where wind data from the meteorological station will be used to analyse and better understand this pattern.

Due to the close relationship between the historical and modern raingauges at sites with no slope, there is no indication of which is more accurate. For this analysis, the correction factors will be chosen for the historical raingauges. Given the variations in the slopes and aspects that the raingauges are installed on and the different relationships across the sites, it is necessary to create correction factors for each site. Table 3.17 shows the calculated correction factors from the data collected up until this report. These correction factors are applied to the historical raingauges. They were determined from trend lines calculated for each site.

Table 3.17: Preliminary correction factors, calculated for each site to be applied to the historical rainfall data

Site	Correction Factor (%)
Mike's Pass Meteorological station	-0.49
IIB	5.99
IIC	-6.65
IIIB	-14.44
IVB	-5.30
VA	-6.14
VIIA	14.6
VIIC	-1.77
VIIIA	-1.58
IXA	6.07
XA	5.22

4. A HYDROLOGICAL MONITORING PLAN FOR THE CATHEDRAL PEAK RESEARCH CATCHMENTS

The socio-economic and environmental importance of the Cathedral Peak area together with its inherent geographical complexity and the fact that mountains represent unique areas for the detection of climatic change and the assessment of climate-related impacts (Beninston, 2003), means that it is crucial to develop a representative, sustainable long-term hydrological monitoring plan which is compatible with the historic Cathedral Peak research catchments network and relevant for future climate change monitoring.

4.1 Challenges Faced in Monitoring Mountain Weather and Climate

Any attempt at investigating the dynamics of mountain climates is complicated (Barry, 2008). The reasons for such complications are diverse. Inherently, weather phenomena in mountains are distinctly more variable and severe compared to low lands (Cegnar, 2005, Thompson *et al*., 2009), reflecting an order of environmental controls on a number of meteorological elements (Buytaert *et al*., 2006; Barry, 2008). An additional issue is the varying scales at which these controls function. On a regional scale, insolation and atmospheric circulation may determine the prevailing climatic patterns whereas altitude and a number of local factors such as aspect and exposure may determine climatic dynamics at finer scales (Barry, 2008). The topography of mountain environments therefore set up such a variety of local weather conditions that any meteorological station is only representative of a limited area (Cegnar, 2005).

Additionally, measuring meteorological parameters in mountains is not an easy task mainly because of severe climate, remoteness and relatively expensive measuring instruments and maintenance (Cegnar, 2005). Meteorological stations are typically positioned in open terrain away from any barriers to airflow (Barry, 2008). In mountain regions, however, you have to consider a number of geographical features such as a summit, slope and valley bottom, apart from the consideration of slope, slope orientation, slope angle and irregularities of small scale relief (Becker and Bugmann, 1999). Also, representative meteorological stations are usually located in valleys where weather generating systems and resultant spatial patterns of rainfall are different to those operational at higher elevations (Prudhomme and Reed, 1998). This, in turn, results in unique thresholds for change between different ranges (Huber, 2005). For these reasons the uncertainty surrounding environmental change and the associated impacts on the hydrological system, is a problem which is compounded by the natural climatic and geographical complexity of high altitude catchments.

4.2 Monitoring for Global Change

The need for quality, long-term datasets has become more important and apparent with the current impacts of anthropogenic activities on the environment, the increasing demand for environmental resources and services (e.g. Parr *et al*., 2003; Rast *et al*., 2014) and the need for decision making to be based on a sound understanding of the hydrological processes (Gomani *et al.*, 2010). Beyond this long-term datasets are essential for detecting and understanding global change (Parr *et al*., 2003).
These long-term datasets can only be obtained through establishing suitable, sustainable hydrological monitoring networks that adequately characterize the properties, distribution, and

circulation of water in the atmosphere (vapour fluxes, precipitation), on the land (soil moisture, overland flow, groundwater), and in surface waters (rivers, reservoirs, wetland storage). All components of the hydrological cycle and local climate need to be monitored, and topography, soil properties and plant physiology documented to be able to detect changes and facilitate a comprehensive understanding of the complex water processes, the mechanisms and magnitudes of feedbacks between local interferences and the hydrological cycle (Rast *et al.*, 2014), and thresholds of change. An appropriate and relevant scale for this monitoring is the catchment scale as it constitutes a geographical unit for which water budgets can be reasonably well closed (Bring and Destouni, 2011). Although monitoring networks should be designed and implemented in as rigorous manner as possible, they may not encompass all processes and feedbacks, and additionally the spatial coverage of monitoring networks is often limited. However, the value of the monitoring data becomes even more apparent in the development and validation of more realistic process-based models that can further improve our understanding, allow transfer of understanding to data scarce areas and forecast impacts of change (Parr *et al*., 2003).

Long-term, consistent and continuous monitoring is particularly needed in high altitude catchments where few measurement series exist, and those that do are of short duration. Furthermore, observation networks are needed in catchments with near-natural conditions (Whitfield *et al.*, 2012) and in catchments that allow for the understanding of processes involved in the recovery of systems from damage (Parr *et al*., 2003). The Cathedral Peak research catchments are ideal as a long-term monitoring site for global change as they are high altitude catchments, have catchments both in pristine and damaged condition (previously afforested catchments), and have a long historical record (although interrupted).

The monitoring plan for the catchments will need to cover surface and groundwater quantity and quality monitoring, as well as the circulation of water in the atmosphere (fluxes, precipitation), movement of water within in the soil profile and interactions of water and land. The hydrological data collection must be accurate, and carefully documented with adequate metadata (Whitfield *et al.*, 2012). Beyond the use of traditional monitoring methods, modern technologies must be considered. These modern techniques should be used to reduce uncertainties associated with monitoring, while not undermining and detracting from the importance of maintaining, strengthening and ensuring good quality datasets.

4.3 Summary of the Historical Monitoring Network

An inventory of the past measurements, including record lengths and equipment, was provided in Chapter 3.1 for all fifteen Cathedral Peak research catchments. This section summarises the historical monitoring network prior to the proposal of the future monitoring network for the catchments. As the reestablishment of monitoring in the catchments is only considering catchments 1-X, only the historical network for those catchments will be summarised.

The primary climatological measurements for the catchments were historically made at the Mike's Pass meteorological station (Figure 3.1) and supplemented with rainfall measurements taken at 24 sites distributed through the 10 catchments (Figure 3.1). Streamflow monitoring was undertaken at weirs located at the outlets of the 10 catchments as shown in Figure 3.1. Beyond the climatological and streamflow monitoring, more focused hydrological monitoring campaigns were undertaken in Catchment VI. Two boreholes were drilled and monitored in Catchment VI at the locations shown in Figure 3.1 and evaporation was monitoring for short periods at near site indicated in Figure 3.1. Historically, intensive monitoring campaigns and the research focus has often been on Catchment VI, a pristine grassland catchment.

4.4 Proposed Hydroclimatological Monitoring Plan for the Cathedral Peak Research Catchments

The challenge of dealing with change is not new to hydrological science; however approaches to dealing with change rely on the assumption of stationarity (Sivapalan *et al*., 2003; Wagener *et al*., 2010). Under the assumption of stationarity, historical observations could be used to project into the future. However, with environmental change this assumption of stationarity may no longer be valid (Wagener *et al*., 2010). Due to changes in the environment, the hydrological system may exhibit changes in behaviour that have not been observed previously due to thresholds, shifts in feedback dynamics and tipping points in the system being reached (Ngcobo *et al*., 2013; Thompson *et al*., 2013). Thus, although a wealth of historical data from the Cathedral Peak catchments already exists there is an urgent need to continue monitoring into the future, with the necessary enhancements in the monitoring network to ensure that change and its impacts are also adequately catered for. Long-term monitoring is the foundation for the research plan developed for the Cathedral Peak research catchments (Figure 4.1) and the platform from which research towards an improved understanding of the hydrological processes and the thresholds and tipping points of the hydrological system can be undertaken.

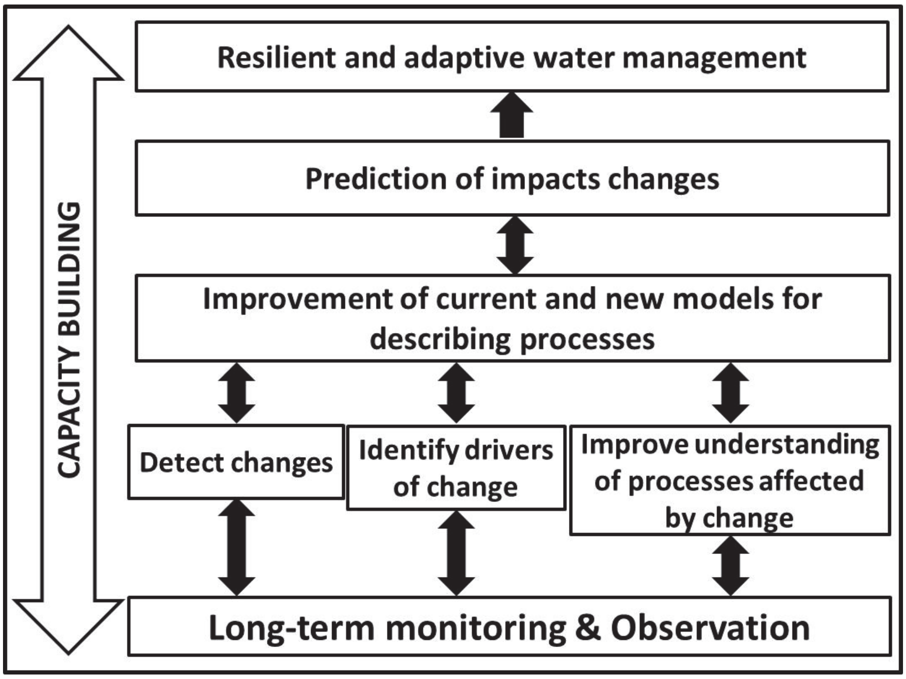

Figure 4.1: Long term monitoring as the foundation for improved understanding and the facilitation of resilient water management

The hydrological monitoring network needs to be comparable with the historical network to benefit from the historic data for change detection and identification of drivers of change as well as being relevant for monitoring changes and thresholds or tipping points in system behaviour into the future. Meeting this requirement requires foresight to combine improvements and new approaches to observation and monitoring while maintaining compatibility with historic data. The datasets need to be available and compatible to further develop hydrological models that have a greater consistency with the real world, incorporating improved process understanding. In addition, the proposed monitoring needs to fulfil the requirements that researchers will have in the future when addressing environmental change. Thus, the monitoring plan for the Cathedral Peak catchments proposed here is to have catchment wide climatological monitoring, streamflow monitoring in key catchments and then focused, detailed monitoring in Catchment VI with the full array of evaporation, soil moisture and groundwater monitoring.

4.4.1 General climatological monitoring

To be able to detect changes in climate, to have the required climatological inputs to hydrological (and other) models it is necessary to have a full automatic weather station at the Mike's Pass meteorological station and to continue with the historical array of raingauges in the catchment.

The new automatic weather station has been installed at the old meteorological site at the top of Mike's Pass. At this site, net radiation (NRLite, Kipp & Zonen, Delft, The Netherlands), wind speed and direction (Model 03002, R.M. Young, Traverse city, Michigan, USA), air temperature and humidity (HMP60, Vaisala Inc., Helsinki, Finland), rainfall (TE525, Texas Electronics Inc., Dallas, Texas, USA) and ultra-violet radiation (SU-100, Apogee Instruments, Inc., Logan, UT 84321, USA) are monitored. The climatic data are averaged over 5-min intervals from observations made every 10 s and stored on a datalogger (CR1000, Campbell Scientific Inc., Logan, Utah, USA). The raingauge orifice is at 1.2 m above the ground and all other sensors are located 2 m above the ground. In addition, a fog collector of a similar Juvik/louvered screen gauge design was installed at the Mike's Pass meteorological site (Figure 4.2) in April 2014 and an additional fog gauge in Catchment VI to allow the contribution of fog to catchment precipitation to be estimated.

In catchments IV to VII, Texas rainfall stations (TE525, Texas Electronics Inc., Dallas, Texas, USA) have been installed with the orifice at 1.2 m above the ground at the same sites that the historic raingauges were located. The rainfall resolution is 0.254 mm and is recorded on a datalogger (Hobo Pendant Event UA-003-64, MA, USA). In catchments I to III and catchments VIII to X, Davis raingauges (Model 7852, Davis, CA, USA) have been installed at the historical sites. An aim of this project (Chapter 6), was to improve the understanding of the rainfall distribution and its characteristics across the Cathedral Peak catchment. The work undertaken to achieve this aim has shown that there is a strong directional influence on long term average and dry season rainfall with rainfall ranging from 1300 mm in the east, to over 1700 mm p.a. in the South West. While during the wet season the influence of altitude was also evident (*c.f.* Chapter 6). These findings confirm the need to retain the 24 raingauges through the catchments, covering a range of longitudes and altitudes. It is recommended that additional wind stations be installed through the catchments given the relationship between wind and rain, and wind and evaporation.

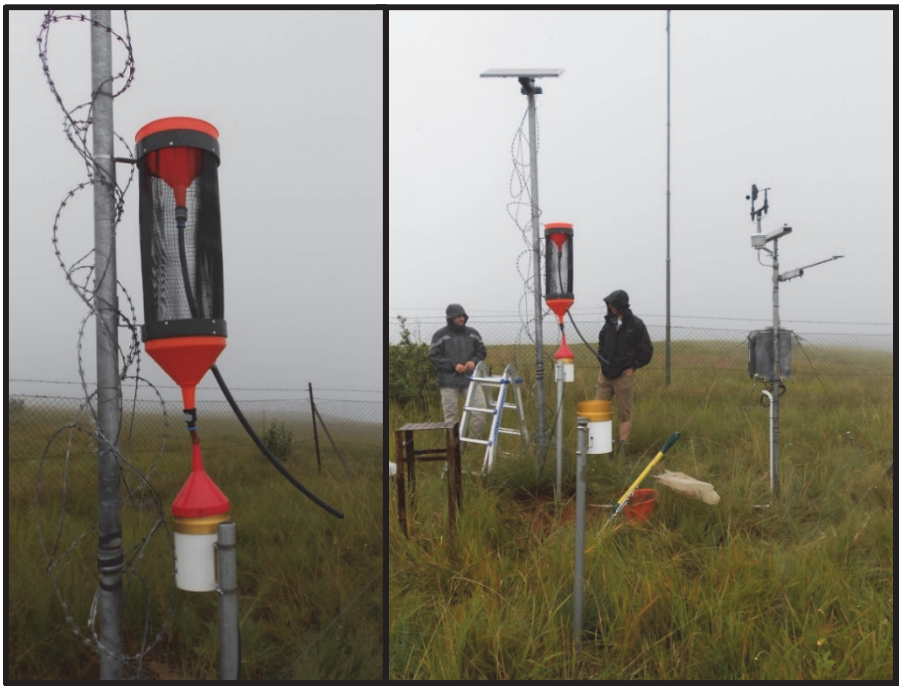

Figure 4.2: The design of the fog collector installed alongside a Rain Gauge and an AWS at Mike's Pass meteorological station

4.4.2 General streamflow monitoring

Streamflow monitoring was historically undertaken at the outlet of each catchment. Given the aim of ensuring the sustainability of the monitoring network and the costs associated with weir maintenance it was recognised that streamflow monitoring needed to be rationalised. Given the focused studies in Catchment VI, the streamflow at the outlet of this catchment needs to be monitored. To further support baseline studies, model development and process understanding the streamflow at the outlets of Catchments IV, V and VII will be monitored. Given the need to understand the influences of change, resilience and process understanding under change the streamflow at the outlets of Catchment III which was previously an afforested catchment and Catchment IX which is a fire exclusion catchment will be monitored.

Since maintenance of the weirs ceased in 1995, the weirs silted up with soil and organic material. During 2012 and 2013 the weirs at catchment outlets IV to VII were cleaned out and with some minor repairs to the structures and stilling wells, and were found to be operable. Measurement of the water stage-height (Orpheus Mini, Ott Hydromet GmbH, Germany) at catchments IV to VII has been implemented using hourly monitoring with breakpoint recording (0.002 mm). The weir at the outlet of catchment III was cleaned during 2015, and monitoring will commence in 2016. Plans have been made for the weir at the outlet of catchment IX to be cleaned out and repaired in the future.

4.4.3 Focused monitoring in Catchment VI

To allow for studies to improve process understanding and the influences of change, it is necessary to be able to close the hydrological cycle thus monitoring of evaporation, soil moisture and groundwater is needed in Catchment VI. Beyond this, to address more complex questions, carbon flux measurements, water quality monitoring and various other focussed studies many be required. To address these requirements, the boreholes in Catchment VI have been located and monitoring will commence at those sites.

A full open path eddy covariance system (OPEC, Campbell Scientific Inc., Logan, Utah, USA) has been installed in the catchment VI, where, in the early 1990s Bowen ratio and eddy covariance data were collected (Everson *et al*., 1998). This system measures total evaporation rates, albedo and carbon flux which are both critical components of the ecological area and, especially the latter, critical to our understanding of climate change. Linked to the eddy covariance system are soil moisture sensors. Funding obtained through the NRF Strategic Research Infrastructure Grant facilitated the purchases of a Licor 8100 system for measuring long term soil gas flux. In combination, these systems will allow for detailed in site measurements on various components of the carbon cycle.

In addition, the research area has provided the perfect opportunity to test cutting edge equipment recently funded by the Partnerships for Enhanced Engagement in Research (PEER) Science grant by the United States Agency for International Development (USAID), in partnership with the National Science Foundation (NSF). This includes a cosmic ray soil water probe, which is an instrument which measures soil water and has the potential to provide hydro-meteorologists with new methods of evaluating surface soil water across extensive areas. This will be tested in conjunction with a large aperture scintillometer (LAS MkII ET system, Kipp & Zonen, Delft, The Netherlands) funded by the Research Infrastructure Support Programmes (RISP) which is able to estimate path averaged energy fluxes.

5. DETECTION OF CHANGES IN THE CATHEDRAL PEAK REGION

Increased awareness of the potential impacts of climate change has focused attention on the importance of long-term trend detection in climatic and hydrological parameters such as rainfall, temperature and streamflow, recognizing them as key indicators of change (Burn and Hag Elnur, 2002). To detect statistically significant trends there is a need to distinguish between natural climate variability and climate change. Climate variability can be defined as fluctuations in the climate above and below a long-term average (Kundzewicz and Robson, 2004). Climate change, on the other hand, is defined as the continuous long-term positive or negative change in average weather conditions over an extended period of time, attributed directly or indirectly to human activities and external forcing (IPCC, 2007; Kundzewicz and Robson, 2004; Gocic and Trajkovic, 2013). Kundzewicz and Robson (2004) and Burn and Hag Elnur (2002) note that change signals are not easily detected when the natural climate of an area is highly variable. Therefore, changes in the rainfall records from the Cathedral Peak catchments may be difficult to detect given the variability of rainfall at high altitudes. Changes in both temperature and rainfall are often noticeable in changes in streamflow regimes (Thorne and Woo, 2011) as well as extreme events such as floods and droughts (Easterling *et al*., 2000). Thus, a review of detection studies for rainfall, temperature and streamflow was undertaken prior to the detection study.

5.1 Literature Review of Changes in Rainfall, Temperature and Streamflow

5.1.1 Trends in Rainfall

Trend detection studies reveal that the observed trends in rainfall patterns are not uniform across the world (Kalumba *et al*., 2013; Burn and Hag Elnur, 2002). Traditionally, rainfall detection studies have focused on the change in rainfall depths such as the mean monthly, seasonal and annual amounts (Frei and Schär, 2001; Easterling, 2000). However, recent studies show that components such as rainfall intensity, event frequency (Shahid, 2011) and shifts in the rainfall patterns (Karl and Knight, 1998; Shahid, 2011; New *et al*., 2006) have become of interest.

On a global scale rainfall extremes have intensified, with parts of the world experiencing more rainfall and others less (Figure 5.1; IPCC, 2007). In general, positive trends have been observed for Canada, Alaska, North and South America, southern Africa, Asia and northern Japan, Europe and eastern Australia. While negative trends have been observed for western Africa, western Australia, parts of the Mediterranean region, South East Asia and the East Indies region.

According to Sayemuzzaman and Jha (2014), observed trends across the United States show increases in rainfall over the past decades. Similarly, Groisman *et al*. (2012) reported increases of 6% during the past century across the United States and statistically significant increases in heavy precipitation over the past 30-40 years in Central America. For Australia, Lavender and Abbs (2013) found that rainfall has increased significantly in the north-west over the past 40 years but decreased in the eastern parts of the country. In agreement with these trends for the eastern parts of the country, Barua *et al*. (2013) showed decreasing annual rainfall trends in the Yarra catchment. No significant trends have been found in annual rainfall across China however, trends at a regional scale are evident. Li *et al*. (2011) found significant increases of 6.01 mm per decade in rainfall over the

Hengduan Mountains during 1960-2008. Similarly, annual rainfall has increased by 10-20% and 5-10% per decade in parts of northwest China and Tibet, respectively, while rainfall has decreased by 5% per decade in northern China (Zhai *et al*., 2005). In Switzerland there has been an observed increase in intense precipitation and average winter rainfall (Frei and Schar, 2001).

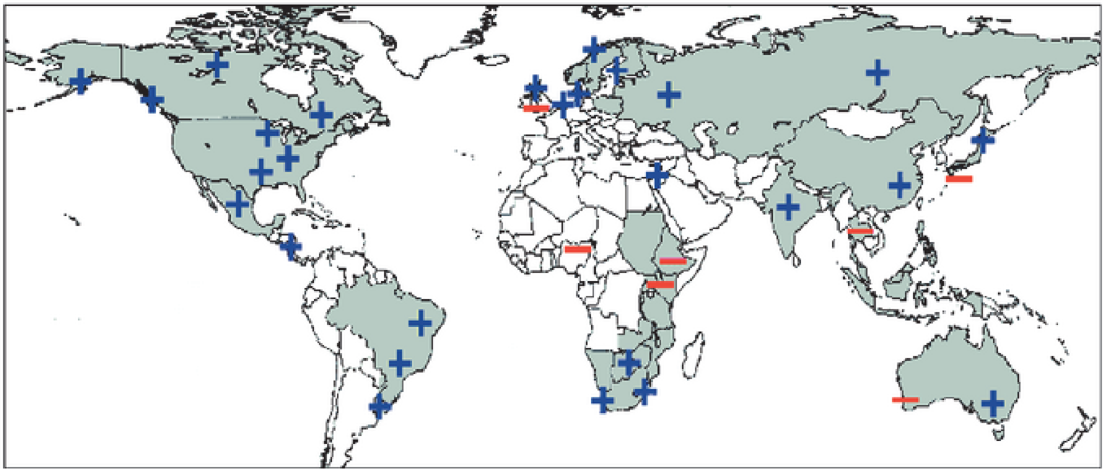

Figure 5.1: Observed changes over the past decades (1951-2003) showing regions where disproportionate changes in heavy and very heavy precipitation were documented as either an increase (+) or decrease (−) compared to the change in annual and/or seasonal precipitation (updated from Groisman *et al*., 2005; IPCC, 2007)

Only a few detection studies have been undertaken in Africa due to limited data and poor data availability. Furthermore, the majority of these studies have been undertaken for the Southern African region. For southern Africa, New *et al*. (2006) reported a general negative trend in rainfall since 1961. Studies conducted at regional scale confirm a decreasing trend but vary in magnitude. Gaughan and Waylen (2012) showed a negative trend in the spatial and temporal rainfall patterns between 1950-1975 and 1980-2005 for the Okavango-Kwando-Zambezi catchment. In Malawi, negative monthly rainfall trends were detected between 1960 and 2006 from 88% of the stations analysed with only four stations showing statistically significant trends. At an annual time scale, 52% of the stations showed negative trends with only two stations being significant (Ngongondo *et al*., 2011). Mason and Jury (1997) reported a 10% decrease in rainfall in midsummer rainfall in northern Botswana, Zimbabwe and eastern South Africa. Similarly, Unganai (1996) showed that Zimbabwe's rainfall has decreased by 100 mm or 10% over the past 100 years. Mazvimavi (2010) disputes these earlier studies for Zimbabwe showing declining rainfall, stating that historical rainfall records from 1892-2000 showed no evidence of change in low, median or high rainfall. Mazvimavi (2010) did not dispute the realities of climate change, however indicated that changes are not yet significant in the observed rainfall record. For South African, Mason and Jury (1997) reported a decrease in mean annual rainfall for the eastern lowveld, as well as an increasing trend in rainfall variability across the country. Similarly, Kalumba *et al*. (2013) showed an increasing inter-annual variability in rainfall. Mason *et al*. (1999) showed significant increases in rainfall and extreme events between 1931-1960 and 1961-1990.

The studies reviewed considered global and continental rainfall trends at different spatial scales with some including mountainous regions. However, the significance of trends in these mountainous regions is often unknown because of a lack of long-term data as a result of sparse observation network due to complex terrain (Kao *et al*., 2013; Haile *et al*., 2009). Studies conducted by Nel and Sunmer (2006) and Nel (2009) for the Drakensberg area considered the seasonal and inter-annual variability of rainfall finding no evidence of rainfall trends. However, no studies have comprehensively assessed long-term trends in high altitude rainfall records.

5.1.2 Trends in Temperature

Atmospheric and climatic changes are mostly detected using temperature variations (Jhajharia *et al*., 2013) as temperature trends are easily examined using average annual temperature, the frequency of extremes of daily minimum and maximum temperatures, and diurnal temperature range (Easterling 2000). Trends in global temperatures have been evident since the beginning of the twentieth century, becoming more pronounced in the mid-century with an observed increase in the average global temperature of approximately 0.6^{o}C since the beginning of the twentieth century and 0.3^{o}C from the mid-century (Kruger and Sekele, 2013; IPCC, 2013).

Temperature trends across southern Africa are similar trends to those observed at a global scale and across the southern hemisphere (Hulme, 1996). According to Jury (2013) temperatures in southern Africa have increased significantly at a rate of 0.4 °C/year. Stronger warming trends have been noted in the western parts of South Africa (Mason and Jury, 1997). Similar warming trends for southern Africa were shown by Hulme (1996); Mason and Jury (1997); Kruger and Shongwe (2004); New *et al*. (2006) and Kruger and Sekele (2013). Kruger and Sekele (2013) indicate general positive trends across South Africa in the average annual, maximum and minimum temperatures as well as an increase in the number of hot days and nights and a decrease in the number of days with low temperatures (thus indicating a decrease in the diurnal range).

Advances in mountain climate research indicate that high altitude regions are highly sensitive and vulnerable to the impacts of climate change (McGuire *et al*., 2012; Behnke 2011; Rangwala and Miller, 2010). The paucity of observation stations and the complex terrain in high altitude areas continues to restrict the number of studies that can be conducted. As a result insufficient attention is given to long-term temporal trends in climatic variables in regions with complex terrain (Barry, 1992; McGuire *et al*., 2012). The limited studies to date show that climate change impacts are significant in high altitude regions with increases observed in daily minimum temperatures but not in maximum temperatures (McGuire *et al*., 2012; Rangwala and Miller, 2010). For example, Kattel and Yao (2013) found annual temperature to be increasing and the diurnal temperature range to be decreasing in the Himalayas particularly for the Tibetan plateau. Rangwala and Miller (2010) showed, for Colorado's San Juan Mountains, an overall increase in mean annual temperature by approximately 1^{o}C between 1895-2005, with a more rapid increase in the last 20 years as well as evidence of a decreasing diurnal temperature trend. The majority of high altitude temperature studies are conducted in the northern hemisphere with a few studies emerging from the southern hemisphere and fewer from African countries. Although, temperature studies have been conducted in South Africa, there is still a lack of focus on mountainous regions which are vulnerable and severely affected by changes in temperature.

5.1.3 Trends in Streamflow

Given the potential impacts of climate change, understanding the long-term historical trends and changes in the hydrological regime is important for water resources management and planning (Westmacott and Burn, 1997; Kingston *et al*., 2009; Stahl *et al*., 2010; Abghari *et al*., 2013). According to Molnár and Ramírez (2001); Stahl *et al*. (2010) and Abghari *et al*. (2013) streamflow observations from pristine catchments are of vital importance for both detection and attribution studies as they reveal more than changes in river flow, they also reflect characteristics of rainfall, vegetation, evaporation and topography, allowing for the detection of long-term trends and abrupt changes which can arise from a combination of direct and indirect factors such as land use change or climatic variability. Furthermore, they reflect the spatially integrated response of the catchment as a single unit (Burn and Hag Elnur, 2002). Streamflow trends are often examined in combination with other climatic variables such as rainfall due to their interdependent nature (Westmacott and Burn, 1997; Sene *et al*., 1998; Molnar and Ramirez, 2001; Burn, 2008; Kingston *et al*., 2009; Thorne and Woo, 2011 and Abghari *et al*., 2013). Often studies examine trends in seasonal, annual as well as maximum and minimum variations in streamflow (Abghari *et al*., 2013). However, advances in change detection studies have highlighted the importance of studying the occurrence of extreme events, especially with climate change predictions forecasting the intensification of extreme events (Frei and Schär, 2001; Kundezwicz and Robson, 2000).

No consensus is evident in streamflow trends at a global scale. Alkama *et al*. (2013) found no significant change in streamflow over the period 1958-1992 for 161 global rivers. While Labat *et al*. (2004) and Dai *et al*. (2009) suggested an increase in global runoff for the past 75 years. Labat *et al*. (2004) showed positive and stable streamflow trends in North America, Asia, South America and Europe and negative trends in Africa. Furthermore, Labat *et al*. (2004) and Dai *et al*. (2009) both reveal a correlation between global temperature and runoff with Labat *et al*. (2004) reporting a 4% increase in streamflow for every $1^{o}C$ temperature increase in parts of North and South America.

A few streamflow studies have been conducted at a continental scale in the northern hemisphere particularly focusing on snow-fed mountainous regions in developed countries where snowmelt contributes to streamflow (Gautam *et al*., 2010, Abghari *et al*., 2013). According to Gautam *et al*. (2010) the lack of reporting of trends in mountainous regions stems from lack of data and the perception that small pristine catchments in mountainous regions have little or no impact on a global scale even though such perceptions may not always hold. However, trends in hydroclimatic variables such as streamflow in small, pristine non-snow-fed mountainous regions in developing countries have recently come under the microscope (Gautam *et al*., 2010), but few studies exist.

Fanta *et al*. (2001) assessed river flow data from 502 gauging stations across nine southern African countries. Findings showed significant positive trends at 96 gauging stations, negative trends at 137 and the remaining 269 showed no trends. The conclusions drawn from this study suggest there has been a decline in mean annual runoff commencing from 1975. Odiyo *et al*. (2011) examined the relationship between rainfall and streamflow in the Luvuvhu River catchment using the 5 and 10 year means from 1931-2006 and revealed increasing variability in both rainfall and streamflow. The overall rainfall record displayed decadal fluctuations and the annual results showed a negative trend in rainfall in the 5 and 10 year means during the study period. However, the streamflow results showed increasing trends which is not consistent with the rainfall trends despite the co-dependent nature of rainfall and streamflow. This inconsistency can be attributed to other confounding factors as a result of anthropogenic activities such as impoundments from urban developments which increase streamflow (Odiyo *et al*., 2011).

The literature reviewed revealed no consensus on streamflow trends. Although many studies consider streamflow variability, only a few report on the actual trends that have been observed. This highlights the need to increase the number of gauging weirs to improve our understanding streamflow trends, particularly in mountainous, pristine areas which contribute significantly to streamflow, which will inevitably affect water resources management and planning (Westmacott and Burn, 1997; Kingston *et al*., 2009; Stahl *et al*., 2010; Abghari *et al*., 2013).

5.2 Methodology and data used

To achieve the objective of determining whether trends in rainfall, temperature and streamflow are evident in the Cathedral Peak area, the approach followed comprised of four main stages, namely data quality control, exploratory or visual analysis, application of statistical tests and lastly the interpretation of trends. Quality control is an essential component of the first and second stage which includes obtaining and preparing the data in order to compile a suitable dataset for analysis (Shahid, 2011; Kundzewicz and Robson, 2004; Easterling *et al*., 2000). During this stage, elements such as the record length, time step and missing data values are important to consider in the preparation of the dataset in order to compile a complete record (Kundzewicz and Robson, 2004). These elements influence the accuracy and quality of the data and have an effect on the subsequent stages.

The subject of record length is a recurring challenge in detection studies (Dixon *et al*., 2006). In a study conducted to investigate the effect of record length on the detection of hydrological trends Dixon *et al*. (2006) found that statistically significant trends were more confidently detected in longer record lengths as opposed to shorter record lengths. In a Canadian study by Burn and Hag Elnur (2002) a minimum record length of 25 years was specified to reduce the any shortcoming associated with using shorter record lengths. Dixon *et al*. (2006) and Kunzdewicz and Robson (2000) advocate for the use of the longest data record available.

5.2.1 Rainfall Data Collection and Quality Control

Data quality control is an essential component of the methodology as it determines the validity of the dataset which will subsequently allow for the compilation of an adequate dataset for the accurate detection of trends in the data (Kundzewicz and Robson, 2004). The rainfall data used for the detection study was taken from two separate time periods namely, historical and current. The historical time period was between 1948 and 1997 and the current time period was from 2013 to present. The initial historical daily rainfall dataset was assessed for inaccuracies and found to contain errors and missing values therefore, had to be patched as explained in Chapter 3.2. The current daily rainfall data was complete with no major in accuracies or missing values and did not need to be patched. Table 5.1 provides details on the start and end dates, time steps and length of the record for both the historical and current rainfall.

Table 5.1: Details of the historical and current rainfall data used for the detection study

Gauge	Historical Rainfall Record				Current Rainfall records			
	Start date	**End date**	**Length (yrs)**	**Time Step**	**Start date**	**End date**	**Length (months)**	**Time Step**
IA	Aug 1950	Sep 1985	35	Monthly				
IC					Nov 2013	July 2015	18	Daily
IIA	Aug 1948	Feb 1993	45	Monthly	Nov 2013	July 2015	18	Daily
IIB	Dec 1988	Feb 1993	5	Monthly	Oct 2013	July 2015	21	Daily
IIC	Jan 1949	Feb 1993	46	Monthly	Nov 2013	July 2015	18	Daily
IIIA	Aug 1950	Oct 1990	40	Daily	Nov 2013	July 2015	18	Daily
IIIB	Jan 1990	Oct 1990	0	Monthly	Nov 2013	July 2015	18	Daily
IVA	Jan 1949	Dec 1987	38	Daily	Sep 2013	July 2015	22	Daily
IVB					Jan 2014	July 2015	18	Daily
IVC	Dec 1988	Feb 1993	5	Monthly	Dec 2013	July 2015	19	Daily
VA	Aug 1950	Feb 1993	43	Monthly	Sep 2013	July 2015	22	Daily
VIB	Nov 1972	Oct 1985	13	Daily	Sep 2013	July 2015	22	Daily
VIIA	Oct 1972	Feb 1993	25	Daily	Sep 2013	July 2015	22	Daily
VIIB	Aug 1980	Oct 1985	5	Monthly	Nov 2013	July 2015	18	Daily
VIIC	Aug 1980	8Aug 1990	10	Monthly	Sep 2013	July 2015	22	Daily
VIIIA	Oct 1965	Feb 1993	28	Monthly	Nov 2013	July 2015	18	Daily
VIIIC	Oct 1965	Feb 1993	28	Monthly	Nov 2013	July 2015	18	Daily
IXA	Jun 1954	Mar 1989	35	Monthly	Nov 2013	July 2015	18	Daily
IXB	Jun 1954	Mar 1989	35	Monthly	Nov 2013	July 2015	18	Daily
IXC	Oct 1985	Jul 1990	5	Monthly	Nov 2013	July 2015	18	Daily
XA	July 1955	Feb 1993	38	Monthly	Jan 2014	July 2015	18	Daily
XB	Mar 1973	Sep 1985	12	Monthly				
XC	July 1955	Sep 1970	15	Monthly	Dec 2013	July 2015	19	Monthly
Mike's Pass Met.	Nov 1948	Mar 1984	36	Monthly	Nov 2013	July 2015	18	Daily
Office Met.	Oct 1972	Feb 1993	21	Monthly				

5.2.2 Temperature Data

The initial approach undertaken to investigate the historical temperature trends considered two temperature stations namely the Mike's Pass meteorological station (1955-1984) and meteorological station located at the research office (1972-1993) for which the data was obtained from SAEON. An additional 10 temperature stations within a 60 km radius of the Cathedral Peak catchments were further considered for analysis. The additional temperature data was sourced from the "*Database of*

Gridded Daily Temperatures for Southern Africa" by Schulze and Maharaj (2004). Of the ten additional stations, only one temperature station located at the Cathedral Peak Forest (0299417A) site was suitable for analysis as it contained more than 80% observed data for the period 1970-2000. Thus, the historical temperature trends analysis was undertaken using records from three stations.

The current temperature data was also obtained from SAEON for the period 2013-present. Current temperature data was only available for the Mike's Pass meteorological station and the meteorological station located at the research office.

5.2.3 Streamflow data

The historical streamflow data from Catchments III, IV, V, VI, VII and XI was used in the detection study. The infilling and extension of this streamflow data was detailed in Chapter 3.2. Current data was only available for Catchments IV, V, VI and VII as these are the only weirs at which monitoring has been reestablished. Data for the current period spanned from August 2013 to present.

5.2.4 Statistical Tests used for Trend Detection

There are a variety of parametric and non-parametric statistical methods which can be used to evaluate the presence of significant monotonic trends in hydrological and climatic data (Sayemuzzaman and Jha, 2014; Kundzewicz and Robson, 2000; Gocic and Trajkovic, 2013). Parametric tests are usually based on linear models and normal theory. Consequently, the assumptions made for parametric tests which include normality, linearity and independence are commonly violated by hydroclimatic data (Thas *et al*., 1996). Therefore, non-parametric tests are most suitable for hydroclimatic trend analysis as they are more robust and resistant to outliers, missing data and other irregularities in data records (Tesemma, 2009). This section reviews and describes non-parametric statistical tests that have been used to detect monotonic trends in climatic and hydrological data.

5.2.4.1 The Mann-Kendall Non-Parametric Test

The Man-Kendall test is a widely used rank based, non-parametric statistical test (Mann, 1945; Kendall, 1975) which is often selected as a powerful statistical method to detect the significance of trends in hydrological variables such as temperature, streamflow, water quality and precipitation (Yue and Wang, 2002; Abdul Aziz and Burn 2006; Hamed, 2008; Gocic and Trajkovic, 2013 and Sayemuzzaman and Jha, 2014). The Mann-Kendall test statistic S is given and calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} a_{ij}$$

Where Eq. 5.1

$$a_{ij} = sign\left(x_j - x_i\right) = sign\left(R_j - R_i\right) = \begin{cases} 1 & x_i < x_j \\ 0 & x_i = x_j \\ -1 & x_i > x_j \end{cases}$$

and R_i and R_j are the ranks of observations x_i and x_j of the time series, respectively.

The presence of a statistically significant trend is evaluated using the S value. A positive value of S value indicates an upward trend and a negative value indicates a downward trend (Hamed, 2008 and 2009; Gocic and Trajkovic, 2013).

The Mann-Kendall test can be applied to non-uniform hydrological and climatic datasets which are often subjected to missing values and irregularities in the data (Önöz and Bayazit, 2012; Sayemuzzaman and Jha, 2014; Jhajharia *et al*., 2013). This is considered advantageous as there is no need for data transformation prior to the application of the test. The Mann-Kendall is less sensitive to outliers and missing data when compared to its parametric counterparts (Dixon *et al*., 2006). This is because it compares the median rather than the mean as its test statistic is calculated from the sign of differences and not from the value of the variable thus minimizing the influence of outliers (Önöz and Bayazit, 2003). Greater power is achieved for skewness distributions and data below the detection limit can be incorporated without fabrication of false trends (Yue *et al*., 2002; Yue and Wang, 2002; Yue and Wang 2004; Burn, 2008; Hamed, 2008; Ngongondo *et al*., 2011; Shahid, 2011; Gocic and Trajkovic, 2013; Kalumba *et al*., 2013; Duhan and Pandey, 2013).

The Mann-Kendall is also sensitive to seasonality which is often noticeable in streamflow data therefore, it needs to be accounted for before the application of the test (Khalil *et al*., 2001). The Mann-Kendall or Kendall seasonality test has been suggested by various authors such as; Burn and Hag Elnur (2002) and Hamed (2008) to account for seasonality in data. The seasonal Kendall test (Hirsch *et al*., 1982) accounts for seasonality by computing the Mann-Kendall test on each of seasons separately, and then combining the results to produce statistically sound trends. This test eliminates the influence of dependence between seasons but does not remove the correlation effect within seasons (Hamed and Rao, 1998). The advantages of the Seasonal Mann-Kendall test include that it is easy to compute; has few underlying assumptions and results are not affected by outliers. The disadvantages of this method are that it assumes a single linear trend; seasons must be defined; flow adjustments must be done separately and it may not be as powerful in detecting trends as the Mann-Kendall (Hamed and Rao, 1998).

Despite its advantages there are problems associated with the use of the Mann-Kendall test such as the confounding effect of serial or autocorrelation also referred to as serial dependence (Hirsch and Slack, 1984; Yue and Wang, 2002; Duhan and Pandey, 2013). Positive serial or autocorrelation is a random process that describes the correlation or relation between values of the process at different points in time, as a function of the two times or of the time difference (Hirsch and Slack, 1984). This subsequently causes the detection of a significant trend when in fact there is no trend (Hamed and Rao, 1998; Yue and Wang, 2002; Hamed, 2008; Önöz and Bayazit, 2012). Sayemuzzaman and Jha (2014); Yue and Wang (2002); Duhan and Pandey (2013) and Hamed (2008) documented that von Storch (1995) suggests the use of the pre-whitening technique to eliminate the influence of serial correlation on the results of trend tests. The pre-whitening technique which has been used by authors such as Burn and Hag Elnur (2002); Gocic and Trajkovic (2013) and several others, involves the removal of serial correlation from the data by assuming a particular correlation model and performing the statistical test on the uncorrelated residuals (Hamed, 2008 and 2009). This can be regarded as a method to transform the data or normalise it prior to the application of the test.

An alternative method of removing the effect of serial correlation is known as the modified Mann-Kendall (MMK) trend test and was proposed by Hamed and Rao (1998) cited by (Hamed, 2008; Yue and Wang, 2002). The modification of the Mann-Kendall test accounts for the presence of serial correlation between the observed data without having to transform the data (Blain, 2013). Sayemuzzaman and Jha (2014); Sonali and Kumar (2013) and Duhan and Pandey (2013) all noted that although modifications of the Mann-Kendall test may be redundant, such modifications can also been viewed as useful, for example the Sequential Mann-Kendall (SQMK) as an extension of the Mann-Kendall, is able to detect abrupt temporal shifts. Results from the above mentioned studies highlight concerns regarding the application of the Mann-Kendall test to pre-whitened or modified data. The reason being, that trends are often falsely detected which leads to the rejection of the null hypothesis when in fact it is true (Yue and Wang, 2002). To avoid this Duhan and Pandey (2013) suggest that pre-whitening should not be used for samples sizes larger than 70 and magnitudes of trends larger than 0.005 because rejection of the null hypothesis is insignificant. Therefore, conclusions based on the reviews from Duhan and Pandey (2013) and Yue and Wang (2002) suggest that there is no need for the modified Mann-Kendall test as there was no noticeable difference in the significance between the two tests. Furthermore, they found that it is better to apply the Mann-Kendall test on the original dataset rather than the pre-whitened data.

5.2.4.2 Sen's Slope Estimator

The Mann-Kendall statistical test is often used in combination with the Sen's slope estimator test. Studies by Duhan and Pandey (2013) and Sonali and Kumar (2013) have used the Sen's slope estimator technique in collaboration with the Mann-Kendall test to enhance the statistical value of the Mann-Kendall as it does not calculate the magnitude of the trend. For this reason an alternative non-parametric test known as the Sen's slope estimator (Gocic and Trajkovic, 2013; Shahid, 2011) or Theil-Sen approach (Sayenmuzzaman and Jha, 2014) was developed. This method was originally described and introduced by Theil (1950) and Sen (1968; cited by Sayenmuzzaman and Jha, 2014). The Sen's slope estimator is a robust method which detects the slope of the trend, *i.e.* the change per unit time, which is translated to the magnitude of change (Shahid, 2011; Sayenmuzzaman and Jha, 2014, Gocic and Trajkovic, 2013). The Sen's slope estimator is denoted as (Shahid, 2011)

$$Q' = \frac{x_{t'} - x_t}{t' - t}$$

Where Eq. 5.2

Q′= slope between data points $x_{t'}$ and x_t

$x_{t'}$ = data measurement at time t'

x_t = data measurement at time t

The extensive use of Sen's slope together with Man-Kendall in several studies (e.g. Jhajharia *et al*., 2013; Abghari *et al*., 2013; Sonali and Kumar, 2013; Shahid, 2011; Sayenmuzzaman and Jha, 2014) attests to the popularity of this method to quantify the magnitude of the trend. The collaborative use of the Mann-Kendall test and the Sen's slope estimator for identifying monotonic hydrological trends is regarded as well complemented, thus, demonstrating their value as applicable statistical tests to be used to test for significance as well as the magnitude of trends.

5.2.4.3 The Mann-Whitney Test

The Mann-Whitney test is a non-parametric statistical test developed by Mann and Whitney around the same time as the Wilcoxon rank sum test. Hence, the Mann-Whitney test is also known as the Wilcoxon rank sum test and the combined name of Wilcoxon-Mann-Whitney can also be used. Furthermore, they are the equivalent one each other and can also be derived from one another. The Mann-Whitney test is used to determine whether two groups of data from the same population differ in the median or a central value (Helsel and Hirsch, 2002). In this study the Mann-Whitney test was used to determine the difference between the historical data (1948-2000) and the current data (2012-2015). According to Mustapha, 2013 and Nachar, 2008 the Mann-Whitney test is on the most powerful non-parametric tests for testing the difference between populations furthermore is has advantages as it is distribution free and can be applied to small datasets between 10 and 20 observations. The Mann-Whitney test is calculated using the following equation:

$$U = n1n2 + \frac{n2(n2+1)}{2} - R1$$

Where Eq. 5.3

U = Mann-Whitney statistic
N1 = Sample size of group one
N2 = sample size of group two
R1 = Rank of the sample size

5.2.5 Application of Statistical Tests used for Trend Detection

Two periods of temperature, rainfall and streamflow data were available for the trend detection study, a historical data period which ranged in length and a short current data period. Following the review statistical methods used for trend detection the non-parametric Mann-Kendall test and Sen's slope estimator were selected to detect the presence and magnitude of monotonic trends in the historical data. The Mann-Kendall and the Sen's slope estimator were the preferred statistical tests because they can be applied to non-uniform datasets which are common in hydroclimatic datasets as they are often subject to discontinuities and missing values. As the Mann-Kendall is distribution free, data does not need to be transformed prior to the application of the test and it is less affected by outliers. Serial or autocorrelation in seasonal data is a recurring topic in trend detection studies therefore, to account for this data was separated in to seasonal groups to maintain homogeneity and the Mann-Kendall test was applied to each seasonal group to generate seasonal results.

Due to the short length of the current record an event based analysis previously used by Nel (2008) was carried out and the Mann-Whitney test was applied to test for the difference in the historical and current data. The events chosen varied depending on the hydroclimatic variable. The results from the detection study are presented in the sections which follow.

5.3 Detection of Changes in Rainfall Records

The Mann-Kendall test together with Sen's slope estimator was used to detect trends in the daily, monthly, annual and seasonal rainfall totals for the historical raingauges in the research area. Following this, the Mann-Whitney test was used to detect significant differences between the historical and current rainfall datasets. The Mann-Kendall, Sen's Slope estimator, and Mann-Whitney tests were conducted at the 95% confidence interval and a significance level (p value) of 5%. The premise for a statistically significant trend is one that accepts the null hypothesis: H_o that there is a trend given that the p value is less than or equal to 0.05. Consequently, rejecting the alternative hypothesis: H_a that there is no trend.

5.3.1 Changes in the historical rainfall records

Trends at a daily, monthly, annual and seasonal time scale were considered. Daily rainfall records were only available for seven raingauges of which five were located in the catchments and the remaining two were the Mike's Pass meteorological station and the Office meteorological station situated outside of the catchments at lower altitudes. The Mann-Kendall test showed statistically significant trends for five of the seven daily raingauges (Table 5.2). Raingauges IVA, VIB, and VIIA and the Office meteorological station have significant negative trends, with a decline of 0 mm, 0.000046 mm, 0.000046 mm and 0.000127 mm per day respectively over the period 1949 to 1993. These raingauges are located in the interior of the catchment, quite close to each other, except for office meteorological station (Figure 5.2). Gauge IXA, located on the eastern side of the research area (Figure 5.2), had a positive trend with an increase of 0.000145 mm per day (Table 5.2). No significant trends were detected for gauge IIIA and Mike's Pass meteorological station at a daily time step (Table 5.2).

Table 5.2: Results of the Mann-Kendall test and Sen's slope estimator applied to the daily rainfall records from the Cathedral Peak catchments

	MK Test (S)	P value	Sen's slope	Trend
IIIA	-499797	0.353	0.000085	No Trend
IVA	-5247167	< 0.0001	0.000000	Trend (-)
VIB	-2675283	< 0.0001	0.000046	Trend (-)
VIIA	-9576092	< 0.0001	0.000046	Trend (-)
IXA	1850648	< 0.0001	0.000145	Trend (+)
Mike's Pass	-199366	0.654	0.000104	No Trend
Office	-604440	0.001	0.000127	Trend (-)

Much of the rainfall data from the Cathedral Peak research catchments was recorded at a monthly time step. Given this, rainfall data from 23 raingauges was available for the monthly and annual analysis for the period 1949 to 1997. Twelve of the 23 raingauges showed statistically significant trends (Table 5.3). Raingauges IA, IIA, IIIA, IIIB, IVA, IVC, VA, VIIA, VIIB, VIIIC and IXC showed statistically significant negative trends. The negative monthly trends shown for gauges IVA and VIIA were consistent with the negative rainfall trends at a daily time step. A statistically significant positive trend was shown for gauge XA which could be attributed to the difference in the rainfall feeding mechanisms as literature reveals that the majority of the catchments are feed by an orographic system whereas rainfall, for catchment X which lies on the leeward slope, may result from a frontal system. No trends were found in the annual data (Table 5.3).The Sen's Slope estimate for raingauges with significant trends varied between 13.9 mm and 17.0 mm per month (Table 5.3).

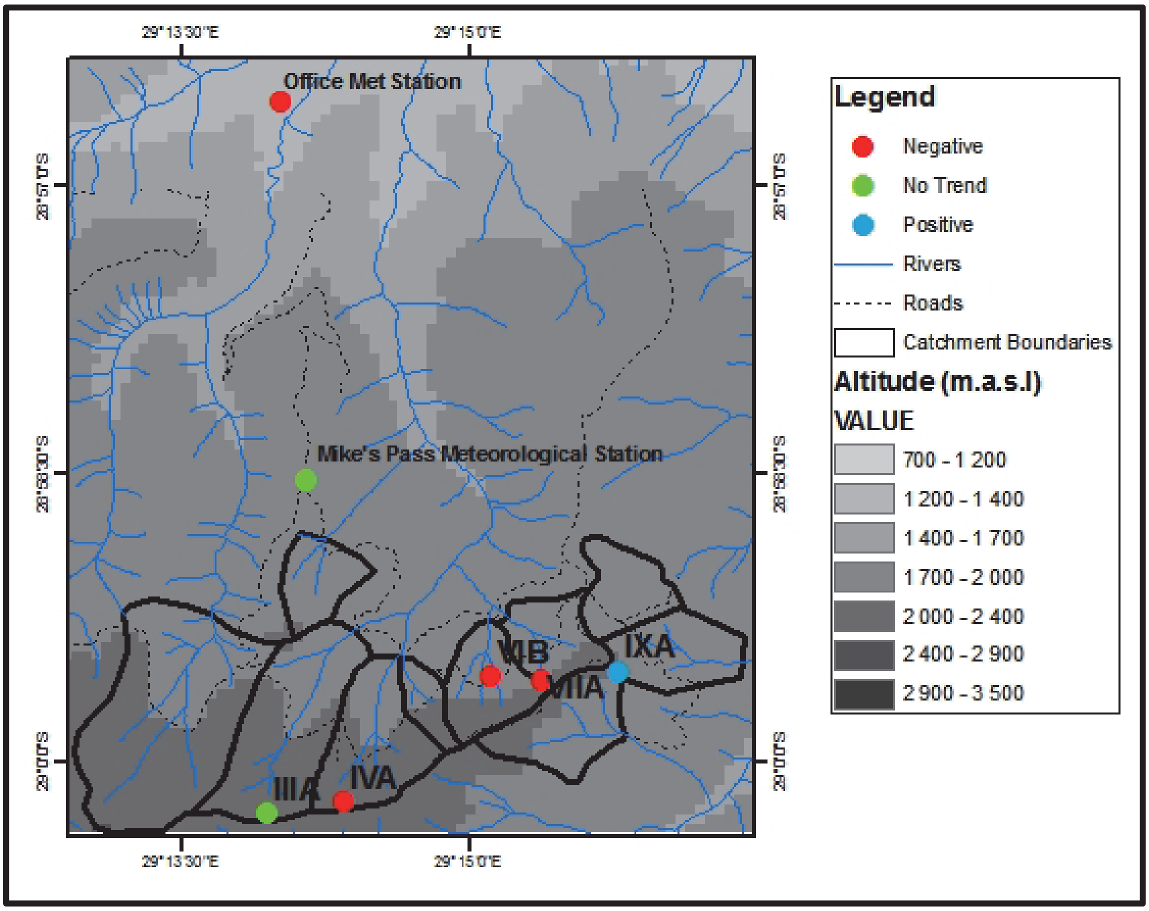

Figure 5.2: Spatial representation of daily rainfall trends in the historical daily rainfall

The significant trends found in the historical rainfall records were primarily evident at the daily time scale. This could be as a result of aggregating the daily rainfall values to monthly and annual totals. The majority of the significant trends detected at the monthly scale indicated a decrease in rainfall, to investigate this further an analysis of seasonal trends was undertaken.

Serial correlation which occurs as a result of seasonality has been highlighted by various authors (e.g. Hamed and Roa, 1998 and Yue and Wang, 2002). To account for this, the data from each raingauge was separated into seasons viz. summer (December-February), autumn (March-May), winter (June-August) and spring (September-November) generating four seasonal datasets for each of the 23 raingauges. This maintained homogeneity within the seasonal group and eliminated the effect of serial correlation. Thereafter, the Mann-Kendall test was applied. The premise for this test was set that the null hypothesis (Ho) stated that there was a seasonal trend in the times series and the alternative hypothesis (Ha) stated that there was no seasonal trend in the times series.

Table 5.3: Results of the Mann-Kendall test and Sen's slope estimator applied to the monthly and annual rainfall records from the Cathedral Peak catchments

	Monthly				Annual			
	MK Test (S)	P value	Sen's Slope	Trend	MK Test (S)	P value	Sen's slope	Trend
IA	-2830	0,024	-0,139	Trend (-)	-52	0,098	-24,179	No Trend
IIA	-2881	0,021	-0,170	Trend (-)	-46	0,146	-21,758	No Trend
IIB	-1784	0,154	-0,104	No Trend	-48	0,128	-21,953	No Trend
IIC	-1313	0,294	-0,065	No Trend	-38	0,233	-12,224	No Trend
IIIA	-2485	0,047	-0,130	Trend (-)	-42	0,186	-20,025	No Trend
IIIB	-2646	0,034	-0,136	Trend (-)	-48	0,128	-24,24	No Trend
IVA	-2984	0,017	-0,158	Trend (-)	-54	0,086	-27,681	No Trend
IVC	-2850	0,023	-0,133	Trend (-)	-46	0,146	-19,611	No Trend
VA	-2695	0,031	-0,132	Trend (-)	-48	0,128	-21,747	No Trend
VIB	-2443	0,051	-0,121	No Trend	-60	0,055	-22,441	No Trend
VIIA	-2700	0,031	-0,121	Trend (-)	-40	0,209	-19,234	No Trend
VIIB	-2566	0,040	-0,131	Trend (-)	-58	0,064	-22,194	No Trend
VIIC	-1559	0,213	-0,068	No Trend	-54	0,086	-18,981	No Trend
VIIIA	-1125	0,369	-0,047	No Trend	-46	0,146	-10,148	No Trend
VIIIC	-2865	0,022	-0,137	Trend (-)	-54	0,086	-22,458	No Trend
IXA	-2360	0,059	-0,104	No Trend	38	0,233	-14,78	No Trend
IXB	-1116	0,373	-0,041	No Trend	32	0,319	-10,339	No Trend
IXC	-2835	0,023	-0,114	Trend (-)	44	0,165	-17,876	No Trend
XA	2926	0,019	-0,135	Trend (+)	-52	0,098	-21,496	No Trend
XB	2329	0,063	-0,101	No Trend	-46	0,146	-17,705	No Trend
XC	1654	0,186	-0,067	No Trend	-50	0,113	-14,952	No Trend
Mike's Pass	-971	0,438	-0,046	No Trend	-22	0,501	-5,242	No Trend
Office	-683	0.597	-0.015	No Trend	-46	0.146	-15.652	No Trend

No statistically significant trends were detected for summer and winter (Table 5.4). Five significant negative trends were detected for autumn for raingauges IA, IVC, VIB, VIIB and VIIIC indicating a decrease in autumn rainfall of 0.904 mm, 0.887 mm, 0.88 mm, 0.994 mm and 0.984 mm per year, respectively. The only statistically significant trend for spring was a negative trend for gauge IIA with a decline of 1.302 mm in rainfall per year (Table 5.4).

At a seasonal time scale, the results indicate that besides a decline in autumn rainfall there are no trends evident in the seasonal rainfall amounts for the historical period. According to IPCC (2013), evidence of climate change has become greater and more pronounced in recent studies. The above results concur with this study as changes in rainfall were not statistically detectable in the historical records. Given, the lack of significant results a comparative study using the historical and current rainfall data was undertaken to determine if any significant differences between the two groups of data were evident.

Table 5.4: Results of the Mann-Kendall test and Sen's slope estimator applied to the seasonal rainfall records from the Cathedral Peak catchments

	Summer (December-February)				Autumn (March-May)				Winter (June-August)				Spring (September-November)			
	SMK Test (S)	P value	Sen's slope	Trend	SMK Test (S)	P value	Sen's slope	Trend	SMK Test (S)	P value	Sen's slope	Trend	SMK Test (S)	P value	Sen's slope	Trend
IA	-102	0,519	-0,564	No Trend	-308	0,05	-0,904	Trend (-)	-28	0,863	-0,003	No Trend	-250	0,121	-0,788	No Trend
IIA	-20	0,904	-0,151	No Trend	-283	0,072	-1,142	No Trend	-82	0,604	-0,017	No Trend	-337	0,037	-1,302	Trend (-)
IIB	-66	0,678	-0,433	No Trend	-210	0,183	-0,76	No Trend	60	0,707	0,016	No Trend	-190	0,24	-0,629	No Trend
IIC	-18	0,914	-0,116	No Trend	-177	0,262	-0,526	No Trend	56	0,725	0,013	No Trend	-110	0,498	-0,281	No Trend
IIIA	-49	0,759	-0,23	No Trend	-290	0,065	-1,006	No Trend	1	1	0	No Trend	-186	0,25	-0,641	No Trend
IIIB	-46	0,463	-0,639	No Trend	-289	0,066	-0,947	No Trend	-5	0,98	0	No Trend	-232	0,151	-0,676	No Trend
IVA	-100	0,528	-0,575	No Trend	-302	0,055	-1,023	No Trend	-37	0,818	-0,006	No Trend	-266	0,099	-1,03	No Trend
IVC	-106	0,503	-0,582	No Trend	-310	0,049	-0,887	Trend (-)	-28	0,863	-0,002	No Trend	-226	0,161	-0,607	No Trend
VA	-121	0,444	-0,637	No Trend	-288	0,067	-0,885	No Trend	-12	0,944	0	No Trend	-240	0,137	-0,661	No Trend
VIB	-18	0,914	-0,052	No Trend	-330	0,036	-0,88	Trend (-)	21	0,898	0,000636	No Trend	-210	0,193	-0,568	No Trend
VIIA	-289	0,066	-0,746	No Trend	-289	0,066	-0,746	No Trend	-48	0,764	0	No Trend	-229	0,156	-0,667	No Trend
VIIB	-34	0,833	-0,176	No Trend	-338	0,032	-0,994	Trend (-)	10	0,954	0	No Trend	-216	0,181	-0,563	No Trend
VIIC	-86	0,588	-0,447	No Trend	-225	0,153	-0,556	No Trend	3	0,99	0	No Trend	-68	0,677	-0,202	No Trend
VIIIA	-84	0,597	-0,445	No Trend	-159	0,314	-0,379	No Trend	-17	0,919	0	No Trend	0	1	0	No Trend
VIIIC	-52	0,745	-0,145	No Trend	-318	0,043	-0,984	Trend (-)	-91	0,565	-0,036	No Trend	-202	0,211	-0,558	No Trend
IXA	-79	0,619	-0,452	No Trend	-284	0,071	-0,751	No Trend	17	0,918	0	No Trend	-156	0,335	-0,423	No Trend
IXB	-34	0,833	-0,19	No Trend	-224	0,155	-0,567	No Trend	57	0,721	0,014	No Trend	34	0,837	0,091	No Trend
IXC	-114	0,471	-0,559	No Trend	-289	0,066	-0,68	No Trend	-40	0,803	0	No Trend	-254	0,115	-0,623	No Trend
XA	-145	0,358	-0,788	No Trend	-299	0,057	-0,84	No Trend	-46	0,773	0	No Trend	-240	0,137	0,724	No Trend
XB	-97	0,54	-0,521	No Trend	-284	0,115	-0,661	No Trend	-14	0,934	0	No Trend	-160	0,332	-0,392	No Trend
XC	-19	0,909	-0,094	No Trend	-238	0,131	-0,595	No Trend	-47	0,769	0	No Trend	-151	0,351	-0,368	No Trend
Mike's Pass	14	0,934	-0,045	No Trend	-135	0,393	-0,435	No Trend	0	1	0	No Trend	20	0,906	0,078	No Trend
Office	69	0.687	0.267	No Trend	-293	0.069	-0.815	No Trend	59	0.711	0.005	No Trend	-5	0.981	-0.0029	No Trend

5.3.2 Comparison of historical and current rainfall records to assess change

The comparative analysis made use of the relatively long historical daily record and the short current daily record obtained from the reestablished raingauges (approximately 2 years data). The Mann-Whitney test was used to test for a significant difference between the historical and current records, it was conducted at the 95% confidence interval and a significance level (p value) of 5%. The premise for a statistically significant difference considers that the null hypothesis H_0, a difference of location between the two groups, is to be accepted if the p value is less than or equal to 0.05 while the alternative H_a, there is no trend, is rejected. The events chosen for analysis were the number of raindays per season, number of dry days per season, daily maximum rainfall, 2-day maximum rainfall (maximum rainfall occurring in 2 consecutive days) and lastly threshold events which analysed the number of days where the rainfall exceeded 20mm and 30mm per day per season. A rainday in the Drakensberg region is defined as one on which more than 0.5mm of rain is measured (Nel, 2008). A total of 20 raingauges were used for the comparative analysis however, for the daily event based analysis data from the only six raingauges was used because there were only six daily historical raingauges.

The results showed that, for summer, the number of raindays has increased significantly between the historical and current period for raingauge IVA and Mike's Pass meteorological station, while no differences were evident for the remainder of the raingauges (Table 5.5). Raingauge IVA showed a similar increase in the number of raindays in autumn and winter (Table 5.5), correlated to this was the finding of a significant decrease in the number of dry days for this gauge in winter. Additionally, raingauges IIIA and IXA showed significant increases in the number of raindays during winter between the current and historical periods (Table 5.5). No significant differences in the number of raindays in spring were evident between the periods. No significant differences in the number of dry days between the current and historical period were evident for summer, autumn and spring (Table 5.5). Thresholds events exceeding 20mm were found to have increased significantly in summer for raingauges IIIA and IVA, and in autumn for raingauges IIIA, IVA and VIB, while no significant differences were evident for winter and spring (Table 5.5). For rainfall events exceeding 30mm, raingauge IVA showed significant increases in both summer and winter between the historical and current periods, while no significant differences were evident in autumn and spring (Table 5.5).

The analysis of the daily maximum rainfall showed a significant decrease in rainfall between the historical and current period for raingauge IXA, while no differences were evident for the remaining raingauges (Table 5.6). Raingauges IIIA, IVA and VIB showed significant increases in 2-day maximum rainfall between the historical and current period (Table 5.6).

Trend detection studies are often subject to uncertainty because of a lack of precise understanding due to limited data as a result of a lack of observation networks and insufficient theoretical attention given to areas with complex and dynamic relations in weather such as mountains (Beniston, 2010). The complexity and highly variable nature of rainfall in the Cathedral Peak area as well as the difference in record length largely contributed to the inconclusive results obtained from the comparative study. However, despite the short current rainfall record the comparative study remains a useful tool in assessing the difference between the two groups of data.

Table 5.5: Results of the Mann-Whitney test for the comparative analysis of the number of raindays, number of dry days per season and threshold events

	No. of raindays											
	Summer			Autumn			Winter			Spring		
	U	P value	Differ.	U	P value	Differ.	U	P value	Differ.	U	P value	Differ.
IIIA	83	0.983	None	114.5	0.359	None	155.5	0.017	Signif. (+)	68.5	0.657	None
IVA	162.5	0.003	Signif. (+)	161	0.005	Signif. (+)	162	0.005	Signif. (+)	85.5	0.918	None
VIB	141	0.107	None	109.5	0.541	None	104	0.593	None	80	0.944	None
VIIA	147.5	0.03	None	127	0.221	None	104	0.555	None	85	0.918	None
IXA	63.5	0.537	None	110	0.494	None	157.5	0.013	Signif. (+)	65	0.537	None
Mike's Pass	163	0.002	Signif. (+)	109.5	0.474	None	113	0.369	None	62	0.497	None
	No. of dry days											
	Summer			**Autumn**			**Winter**			**Spring**		
	U	**P value**	**Differ.**	**U**	**P value**	**Differ.**	**U**	**P value**	**Differ.**	**U**	**P value**	**Differ.**
IIIA	138	0.112	None	65	0.574	None	16.5	0.012	None	106.5	0.505	None
IVA	93	0.991	None	116.5	0.377	None	5.5	0.004	Sign. (-)	84	0.952	None
VIB	92.5	0.932	None	60.5	0.432	None	74	0.849	None	82.5	0.978	None
VIIA	52.5	0.249	None	42	0.177	None	78	0.801	None	85	0.933	None
IXA	127.5	0.334	None	91	0.932	None	59	0.399	None	107	0.53	None
Mike's Pass	127.5	0.212	None	60	0.434	None	67.5	0.986	None	108.5	0.523	None
	No. of threshold events exceeding 20 mm											
	Summer			**Autumn**			**Winter**			**Spring**		
	U	**P value**	**Differ.**	**U**	**P value**	**Differ.**	**U**	**P value**	**Differ.**	**U**	**P value**	**Differ.**
IIIA	567	0.017	Sign. (+)	573	0.012	Sign. (+)	360	0.717	None	382	0.074	None
IVA	641	0.001	Sign. (+)	552	0.015	Sign. (+)	330	0.974	None	387	0.725	None
VIB	361	0.606	None	432	0.022	Sign. (+)	275	0.933	None	280	0.961	None
VIIA	372	0.545	None	411	0.78	None	367.5	0.961	None	395	0.998	None
IXA	346	0.884	None	374	0.386	None	307.5	0.804	None	155	0.243	None
Mike's Pass	535	0.007	None	442	0.104	None	315	0.678	None	261	0.525	None
	No. of threshold events exceeding 30 mm											
	Summer			**Autumn**			**Winter**			**Spring**		
	U	**P value**	**Differ.**	**U**	**P value**	**Differ.**	**U**	**P value**	**Differ.**	**U**	**P value**	**Differ.**
IIIA	482	0.191	None	510	0.089	None	332.5	0.798	None	358	0.173	None
IVA	553	0.017	Sign. (+)	471	0.178	None	312.5	<0,0001	Sign. (+)	483	0.131	None
VIB	335	0.45	None	375	0.178	None	247.5	0.285	None	340.5	0.467	None
VIIA	372	0.911	None	495	0.233	None	335	0.351	None	507	0.231	None
IXA	292	0.754	None	387	0.339	None	277.5	0.497	None	155.5	0.243	None
Mike's Pass	425	0.206	None	465	0.057	None	290	0.831	None	217	0.894	None

Table 5.6: Results of the Mann-Whitney test for the comparative analysis of total daily rainfall and 2-Day maximum rainfall

	Daily Total			2-Day Maximum Rainfall		
	U	P value	Differ.	U	P value	Difference
IIIA	4421712	0.908	None	164772	<0,0001	Sign. (+)
IVA	850116	0.114	None	105334	<0,0001	Sign. (+)
VIB	3987654	0.187	None	134529	0.001	Sign. (+)
VIIA	5331637	0.833	None	176818	0.062	None
IXA	2461947	0	Sign. (-)	135903	0.87	None
Mike's Pass	2997301	0.075	None	103915	0.944	None

5.4 Detection of Changes in the Temperature Records from the Region and Beyond

Historical temperature records were available from the meteorological station located at the research office (Office meteorological station) located near the entrance to the Cathedral Peak reserve at a lower altitude for the period 1972 to 1993, from the meteorological station at Mike's Pass (named here as Mike's Pass station) at a higher altitude for the period 1955 to 1984 and the Cathedral Peak Forest station (0299417A) for the period 1970-2000. Temperature trend detection was carried out using the Mann-Kendall and Sen's Slope estimator to detect historical trends followed by the application of the Mann-Whitney test to determine significant differences between the current and historical temperature datasets.

5.4.1 Changes in the historical temperature records

Statistically significant positive trends were detected in the daily maximum, minimum and average time series as well as for the maximum monthly temperature from the office meteorological station over the period 1972-1993 (Table 5.7). Statistically significant positive trends were detected only in the daily maximum and daily average time series for the Mike's Pass meteorological station. Furthermore, statistically significant positive trends were detected for the daily maximum and average as well as the monthly and annual minimum time series at the Cathedral Peak Forest (Table 5.7). The agreement of statistically significant positive trends in the daily maximum and daily average temperatures for the three considered temperature records begins to indicate a consistent warming trend for the Cathedral Peak area. The Sen's Slope estimate indicated that the daily maximum, minimum, average and maximum monthly temperatures have increased by 0.00024^{o}C, 0.000044^{o}C, 0.000258^{o}C and 0.008^{o}C per month, respectively, for the Office meteorological station between 1972 and 1993. The Mike's Pass meteorological station daily maximum and daily average temperatures have increased by 0.000112^{o}C and 0.000073^{o}C per day, respectively. The daily maximum, minimum and mean temperature have increased by 0.000095^{o}C, 0.00001^{o}C, 0.000091^{o}C per day and the monthly and annual minimum temperatures have increase by 0.005^{o}C per month and 0.12^{o}C per year at the Cathedral peak Forest (Table 5.7).

To investigate this warming trend further, an analysis of the frost occurrences was undertaken. However, no significant trends were detected in the occurrence of frost at the Mike's Pass and Office meteorological stations, while a negative trend was detected at the Cathedral Peak Forest station (Table 5.7).

Table 5.7: Results of the Mann-Kendall test and Sen's slope estimator applied to the temperature records from the Cathedral Peak area

	Office Station				Mike's Pass Station				Cathedral Peak Forest			
	MK Test (S)	P value	Sen's Slope	Trend	MK Test (S)	P value	Sen's Slope	Trend	MK Test (S)	P value	Sen's Slope	Trend
Daily Max	1089865	<0,0001	0,00024	Trend (+)	981009	0,007	0,000112	Trend (+)	1187785	0,003	0,000095	Trend (+)
Daily Min	501076	0,011	0,000044	Trend (+)	545147	0,138	0,000058	No Trend	2463084	<0.0001	0,000010	Trend (+)
Daily Mean	1591379	<0,0001	0,000258	Trend (+)	768257	0,037	0,000073	Trend (+)	1938844	<0.0001	0,000091	Trend (+)
Monthly Max	3302	0,010	0,008	Trend (+)	562	0,798	0,000031	No Trend	3012	0,209	0,002	No Trend
Monthly Min	782	0,545	0,002	No Trend	1031	0,639	0,000930	No Trend	5361	0,025	0,005	Trend (+)
Annual Max	28	0,381	0,062	No Trend	-5	0,943	0	No Trend	45	0,454	0,025	No Trend
Annual Min	13	0,697	0,04	No Trend	4	0,957	0	No Trend	199	0,001	0,123	Trend (+)
Frost Events	-76512	0.0.73	0	No Trend	75888	0,351	0	No Trend	-380404	<0.0001	0	Trend (-)

Seasonal Temperature Trends

	Office Met Station				Top Met Station				Cathedral Peak Forest			
	MK Test (S)	P value	Sen's Slope	Trend	MK Test (S)	P value	Sen's Slope	Trend	MK Test (S)	P value	Sen's Slope	Trend
Summer Max	-7757	0,013	-0,001	No Trend	209549,0	<0.0001	0,000485	Trend (+)	45650	0,377	0,000123	No Trend
Summer Min	44468	<0.0001	0,001	Trend (+)	126919,0	0,009	0,000161	Trend (+)	377037	<0,0001	0,000344	Trend (+)
Autumn Max	171576	<0.0001	0,001	Trend (+)	5713	0,903	0	No Trend	4257	0,933	0	No Trend
Autumn Min	42980	0,112	0,000244	No Trend	72207,0	0,124	0,000122	No Trend	62165	0,221	0,000089	No Trend
Winter Max	32000	0,014	0,000873	Trend (+)	41626,0	0,364	0,000089	No Trend	202590	<0,0001	0,000352	Trend (+)
Winter Min	76526	0,002	0,000407	Trend (+)	-97853,0	0,033	-0,000163	Trend (-)	352690	<0,0001	0,000448	Trend (+)
Spring Max	27306	0,235	0,000309	No Trend	11809,0	0,793	0	No Trend	99109	0,047	0,000318	Trend (+)
Spring Min	25743	0,28	0,000133	No Trend	-58948	0,192	-0,000128	No Trend	301221	<0,0001	0,000438	Trend (+)

In order to eliminate the effect of seasonality, the temperature data was separated into the four seasons, *viz*. summer (December-February), autumn (March-May), winter (June-August) and spring (September-November), generating four seasonal datasets for each temperature station. Thereafter, the Mann-Kendall test was used to analyse the data record. For the office meteorological station (Table 5.7) statistically significant positive trends were detected for the summer minimum, autumn maximum temperatures and winter maximum and minimum temperatures. Statistically positive trends were found for the Mike's Pass meteorological station for summer maximum and minimum temperatures, with a statistically significant negative trend evident in the winter minimum temperatures. Analysis of the Cathedral Peak Forest station records showed statistically significant positive trends in the summer minimum temperatures and the maximum and minimum temperatures for both winter and spring. Although the significant trends detected translate to less than 1^{o}C of change, the rising temperatures are an indication of the global warming impacts regarded as drastic changes for mountainous climates.

5.4.2 Comparison of historical and current temperature records to assess change

A comparative analysis which tested for the difference in threshold events, frost events and mean monthly temperatures between the historical and current temperature records from the Mike's Pass meteorological and Office meteorological station using that Mann-Whitney test was undertaken. No difference in the number of days where the maximum temperature is greater than 30^{o}C was evident in summer at the Mike's Pass meteorological station (Table 5.8). However, an increase in the number of days where the maximum temperature is greater than 30^{o}C was evident in autumn, while on the other hand a decrease was evident in winter and spring. At the Office station the results show that there is no significant difference in the number of days where the maximum temperature is greater than 30^{o}C in summer, while a significant decrease was detected for autumn, winter and spring.

An increase in the number of days where the maximum temperature is greater than 35^{o}C was evident for winter for the Mike's Pass station which may be an anomaly, while the results from summer, autumn and spring were inconclusive (Table 5.8). For the Office meteorological station significant decreases in the number of days where the maximum temperature is greater than 35^{o}C were detected for summer and spring, while the results for autumn and winter were inconclusive. Due to the inconclusive results obtained, an investigation of the raw data was undertaken and revealed that there were a few days where the maximum temperature was greater than 35^{o}C. This suggests that the Mann-Whitney may have not been sufficiently robust to detect the difference due to the low count.

In summer, autumn and spring no difference was evident for the number of days where the minimum temperature is less than 5^{o}C for the Mike's Pass station, while a significant increase 5^{o}C was detected for winter. No difference was detected for the number of frost events in autumn, winter and spring, and the results for the number of frost events in summer were inconclusive at both stations. The mean monthly temperatures appear to have decreased in summer and winter while no difference was detected in autumn and spring at the Mike's Pass station, while there appears to be no significant differences across all seasons at the Office station (Table 5.8).

Table 5.8: Results of the Mann-Whitney test for the comparative analysis of threshold events per season for the Mike's Pass and Office meteorological station

	Mike's Pass Meteorological Station											
	Summer			**Autumn**			**Winter**			**Spring**		
No of days with:	**U**	**P value**	**Difference**	**U**	**P value**	**Difference**	**U**	**P value**	**Difference**	**U**	**P value**	**Difference**
Greater than 30°C	384,5	0,996	No Diff	400,5	<0,0001	Sig Diff (+)	405	<0,0001	Sign. Diff (-)	370	<0,0001	Sign. Diff (-)
Greater than 35°C	400,5	<0,0001	Inconcl.	396	<0,0001	Inconcl.	450	<0,0001	Sign. Diff (+)	478,5	<0,0001	Inconcl.
Less than 5°C	445,5	0,726	No Diff	465,5	0,374	No Diff	711	0,001	Sign. Diff (+)	478,5	0,642	No Diff
Frost events	400,5	<0,0001	Inconcl.	432	0,0903	No Diff	563	0,123	No Diff	572	0,216	No Diff
Monthly Mean	225	0,03	Sign. Diff (-)	285	0,172	No Diff	151	0	Sign. Diff (-)	420	0,28	No Diff
	Office Meteorological Station											
	Summer			**Autumn**			**Winter**			**Spring**		
No of days with:	**U**	**P value**	**Difference**	**U**	**P value**	**Difference**	**U**	**P value**	**Difference**	**U**	**P value**	**Difference**
Greater than 30°C	131.5	0.225	No Diff	71	<0.0001	Sign. Diff (-)	63.5	<0.0001	Sign. Diff (-)	86.5	<0.002	Sign. Diff (-)
Greater than 35°C	161	<0.0001	Sign. Diff (-)	90	<0.0001		90	<0.0001		186	<0.0001	Sign. Diff (-)
Less than 5°C	189	<0.0001		115	0.484	No Diff	122.5	0.34	No Diff	285.5	0.431	No Diff
Frost events	189	<0.0001		94.5	0.277	No Diff	115	0.463	No Diff	256	0.626	No Diff
Monthly Mean	98	0.052	No Diff	92	1	No Diff	86	0.915	No Diff	190	0.386	No Diff

An investigation of the current temperature data from the Office meteorological stations was undertaken following the inconclusive results. The current temperature data was found to have missing values and gaps which were as a result of instrument failure during the recording period. This resulted in a comparison of short current data record to with a much longer historical data record. In addition, a short data record with low count of threshold events may have brought on difficulties which possibly restricted the Mann-Whitney tests' ability to detect any differences.

5.5 Detection of Changes in Streamflow Records

The first analysis of streamflow used the Mann-Kendall test together with Sen's slope estimator to detect daily, monthly, seasonal and annual trends in the historical data (1949-2000) collected at 5 gauging stations in the research area. The second analysis used the historical and current streamflow data (2014-2015) together with the Mann-Whitney test and IHA software, in a comparative study to determine significant differences between the two periods of data.

5.5.1 Changes in the historical streamflow records

Extended streamflow (as described in Section 3.2) from the weirs at the outlets of Catchments III, IV, VI, VII and IX were analysed. Statistically significant negative trends were detected in the daily and monthly streamflow data of each of the streamflow records, with the decline ranging between 0.000029 and 0.000079 $mm.day^{-1}$ and 0.028 and 0.076 $mm.month^{-1}$ (Table 5.9). Statistically significant negative trends for the annual streamflow data were detected for Catchments III, IV, VII and IX. A seasonal analysis was undertaken by separating the data into four seasons *viz*. summer (December-February), autumn (March-May), winter (June-August) and spring (September-November) generating four seasonal datasets for each catchment and applying the statistical tests. Statistically significant negative trends in streamflow were found for summer and autumn for all the gauging stations, and for all gauges in winter except Catchment VI (Table 5.10). For spring, significant negative trends were detected for Catchments III, IV and IX.

To further investigate the declining trend in streamflow an analysis of the historical streamflow was carried out using the Indicators of Hydrological Alteration software (IHA) to calculate certain characteristics of the streamflow from the Cathedral Peak catchments. The historical streamflow data was assessed for changes in the monthly flow rate ($m^3.sec^{-1}$) from January to December as well as the 1-day, 3-day, 7-day, 30-day and 90-day maximum and minimum flows. The results generated (Table 5.11) are consistent with those obtained from the Mann-Kendall test and Sen's Slope estimator (Tables 5.9 and 5.10). Overall the results indicate declining flows in Catchments III, IV and IX, with significant negative trends evident for all variables considered for these three catchments (Table 5.11).

According to Burn and Hag Elnur (2002) and Kalumba *et al*. (2013), how the terrestrial hydrological cycle is altered depends on the change in the climatic factors. Small changes caused by climatic anomalies can have amplified effect on mountainous catchments as they are more sensitive than lowlands (Kormann *et al*., 2014; Fanta *et al*., 2001). Furthermore, land cover and changes thereof can have significant impacts on streamflow. Thus, before determining that the changes evident in streamflow are due to climate and analysis of the land cover changes in the Catchments is required.

Table 5.9: Results of the Mann-Kendall test and Sen's slope estimator applied to the daily, monthly and annual streamflow records from the Cathedral Peak catchments

	Daily				Monthly				Annual			
	MK Test (S)	P value	Sen's Slope	Trend	MK Test (S)	P value	Sen's Slope	Trend	MK Test (S)	P value	Sen's Slope	Trend
III	-58396123	<0.0001	-0.000057	Trend (-)	-63813	<0.0001	-0.054	Trend (-)	-604	<0.0001	-15.153	Trend (-)
IV	-68700684	<0.0001	-0.000070	Trend (-)	-74024	<0.0001	-0.068	Trend (-)	-598	<0.0001	-16.291	Trend (-)
VI	-21364737	<0.0001	-0.000042	Trend (-)	-23586	<0.0001	-0.04	Trend (-)	-198	0.054	-5.681	No Trend
VII	-24884824	<0.0001	-0.000029	Trend (-)	-25139	<0.0001	-0.028	Trend (-)	-276	0.007	-6.621	Trend (-)
IX	-57026390	<0.0001	-0.000079	Trend (-)	-62164	<0.0001	-0.076	Trend (-)	-462	<0.0001	-14.015	Trend (-)

Table 5.10: Results of the Mann-Kendall test and Sen's slope estimator applied to the seasonal streamflow records from the Cathedral Peak catchments

	Summer				Autumn				Winter				Spring			
	MK Test (S)	P value	Sen's Slope	Trend	MK Test (S)	P value	Sen's Slope	Trend	MK Test (S)	P value	Sen's Slope	Trend	MK Test (S)	P value	Sen's Slope	Trend
III	-4489	<0.0001	-0.588	Trend (-)	-4631	<0.0001	-0.548	Trend (-)	-5056	<0.0001	-0.145	Trend (-)	-4292	<0.0001	-0.105	Trend (-)
IV	-4992	<0.0001	-0.675	Trend (-)	-5233	<0.0001	-0.611	Trend (-)	-5301	<0.0001	-0.154	Trend (-)	-3793	<0.0001	-0.115	Trend (-)
VI	-2339	<0.0001	-0.367	Trend (-)	-1737	<0.0001	-0.304	Trend (-)	-607	0.265	-0.035	None	-839	0.123	-0.015	None
VII	-1810	0.001	-0.309	Trend (-)	-2328	<0.0001	-0.299	Trend (-)	-2442	<0.0001	-0.061	Trend (-)	-1053	0.053	-0.031	None
IX	-3723	<0.0001	-0.495	Trend (-)	-4219	<0.0001	-0.538	Trend (-)	-5045	<0.0001	-0.204	Trend (-)	-3541	<0.0001	-0.161	Trend (-)

Table 5.11: Results of the IHA analysis of the monthly flow rates and maximum and minimum from the Cathedral Peak catchments

Monthly Flow Rate ($m^3.s^{-1}$)										
	III		IV		VI		VII		IX	
	P value	Trend	P value	Trend	P value	Trend	P value	Trend	P value	Trend
January	0,005	Trend (-)	0,001	Trend (-)	0,25	No Trend	0,25	No Trend	0,005	Trend (-)
February	0,001	Trend (-)	0,001	Trend (-)	0,25	No Trend	0,25	No Trend	0,005	Trend (-)
March	0,001	Trend (-)	0,001	Trend (-)	0,5	No Trend	0,25	No Trend	0,005	Trend (-)
April	0,001	Trend (-)	0,001	Trend (-)	0,25	No Trend	0,1	No Trend	0,001	Trend (-)
May	0,001	Trend (-)	0,001	Trend (-)	0,25	No Trend	0,025	No Trend	0,001	Trend (-)
June	0,001	Trend (-)	0,001	Trend (-)	0,5	No Trend	0,01	No Trend	0,001	Trend (-)
July	0,001	Trend (-)	0,001	Trend (-)	0,5	No Trend	0,05	Trend (-)	0,001	Trend (-)
August	0,001	Trend (-)	0,001	Trend (-)	0,5	No Trend	0,025	No Trend	0,001	Trend (-)
September	0,001	Trend (-)	0,001	Trend (-)	0,25	No Trend	0,25	No Trend	0,001	Trend (-)
October	0,25	No Trend	0.01	No Trend	0,5	No Trend	0,5	No Trend	0,01	Trend (-)
November	0,025	Trend (-)	0,005	Trend (-)	0,025	Trend (-)	0,25	No Trend	0,001	Trend (-)
December	0,001	Trend (-)	0,001	Trend (-)	0,005	Trend (-)	0,01	Trend (-)	0,001	Trend (-)
Maximum and minimum flow										
	P value	Trend	P value	Trend	P value	Trend	P value	Trend	P value	Trend
1-day min	0,001	Trend (-)	0,001	Trend (-)	0,1	No Trend	0,1	No Trend	0,001	Trend (-)
3-day min	0,001	Trend (-)	0,001	Trend (-)	0,1	No Trend	0,25	No Trend	0,001	Trend (-)
7-day min	0,001	Trend (-)	0,001	Trend (-)	0,1	No Trend	0,5	No Trend	0,001	Trend (-)
30-day min	0,001	Trend (-)	0,001	Trend (-)	0,5	No Trend	0,25	No Trend	0,001	Trend (-)
90-day min	0,001	Trend (-)	0,001	Trend (-)	0,5	No Trend	0,25	No Trend	0,001	Trend (-)
1-day max	0,005	Trend (-)	0,01	Trend (-)	0,5	No Trend	0,5	No Trend	0,025	Trend (-)
3-day max	0,001	Trend (-)	0,001	Trend (-)	0,5	No Trend	0,5	No Trend	0,01	Trend (-)
7-day max	0,001	Trend (-)	0,001	Trend (-)	0,5	No Trend	0,5	No Trend	0,005	Trend (-)
30-day max	0,001	Trend (-)	0,001	Trend (-)	0,5	No Trend	0,25	No Trend	0,001	Trend (-)
90-day max	0,001	Trend (-)	0,001	Trend (-)	0,25	No Trend	0,05	Trend (-)	0,001	Trend (-)

5.5.2 Comparison of historical and current streamflow records to assess change

To date weirs IV, V, VI and VII have been re-established and have begun to monitor streamflow. Given this, data from weirs IV, VI and VII was used in the comparative analysis to evaluate significant differences between the historical (1949-2000) and current (2013-2016) periods. The comparative analysis was carried out using the non-parametric score card which shows a variety of statistics for the pre-impact and post-impact periods from the IHA software and flow duration curves. The non-parametric scorecard tables were calculated using the annual data to reveal a significance count which can be interpreted similarly to a p-value in parametric statistics. A significance count is the fraction of trials for which the deviation values for the medians or coefficient of dispersions were greater than for the real case, thus revealing a difference between the two data groups. A low significance count (minimum value is 0) means that the difference between the historical and current periods is highly significant, and a high significance count (maximum value is 1) means that there is little difference between the periods.

The results from the non-parametric comparative analysis show evidence of a significant decrease in the median monthly streamflow for Catchment IV for the entire year ranging between 0.2745 and 0.995 m^3/s per month for the current period (Table 5.12). A significant decline ranging between 0.9

Table 5.12: Results of the IHA analysis of the median monthly, maximum and minimum flow rates from the Cathedral Peak catchment

Median Monthly Flows									
	Weir IV			Weir VI			Weir VII		
	Significance Count	Significance	Direction of change	Significance Count	Significance	Direction of change	Significance Count	Significance	Direction of change
January	0.6587	Low	Negative	0.46250	High	Negative	0.1512	High	Negative
February	0.2683	High	Negative	0.29630	High	Negative	0.2092	High	Negative
March	0.06106	High	Negative	0.28630	High	Negative	0.1241	High	Negative
April	0.1051	High	Negative	0.16820	High	Negative	0.07107	High	Negative
May	0.04304	High	Negative	0.07808	High	Negative	0.006006	High	Negative
June	0.05806	High	Negative	0.20620	High	Negative	0.01401	High	Negative
July	0.05806	High	Negative	0.12710	High	Negative	0.01602	High	Negative
August	0.06206	High	Negative	0.06406	High	Negative	0.0951	High	Negative
September	0.06206	High	Negative	0.10910	High	Negative	0.1271	High	Negative
October	0.07608	High	Negative	0.08909	High	Negative	0.3253	High	Negative
November	0.1221	High	Negative	0.06707	High	Negative	0.1421	High	Negative
December	0.2823	High	Negative	0.13010	High	Negative	0.1612	High	Negative
Minimum and Maximum Flows									
1-day min	0	High	Negative	0.05105	High	Negative	0.002002	High	Negative
3-day min	0.005005	High	Negative	0.05606	High	Negative	0.003003	High	Negative
7-day min	0.002002	High	Negative	0.1061	High	Negative	0.003003	High	Negative
30-day min	0.001001	High	Negative	0.04805	High	Negative	0.003003	High	Negative
90-day min	0.02803	High	Negative	0.02202	High	Negative	0.009009	High	Negative
1-day max	0.5475	Low	Negative	0.954	Low	Negative	0.3704	High	Negative
3-day max	0.5385	Low	Positive	0.8368	Low	Negative	0.3624	High	Negative
7-day max	0.7828	Low	Positive	0.98	Low	Negative	0.4835	High	Negative
30-day max	0.9409	Low	Positive	0.6637	Low	Negative	0.2923	High	Negative
90-day max	0.6146	Low	Negative	0.5245	Low	Negative	0.3043	High	Negative

and 1 m^3/s was evident in the 1, 3, 7, 30 and 90-day minimum flows, while the 1, 3, 7 and 30 and 90-day maximum flows showed evidence of slight differences between the historical and current period (Table 5.12). A significant decrease in the median monthly flow was evident for Catchment VI, ranging between 0.3048 and 0.6775 m^3/s per month across the entire year (Table 5.12). A significant decline was evident in the 1, 3, 7, 30 and 90-day minimum flows ranging between 0.7024 and 0.9043 m^3/s, while the 1, 3, 7, 30 and 90-day maximum flows showed slight differences between the two periods (Table 5.12). A significant decrease in the median monthly flow was evident for Catchment VII, ranging between 0.4067 and 0.9690 m^3/s per month. A significant decline ranging between 0.4095 and 1 was evident in the 1, 3, 7, 30 and 90-day minimum and maximum flows between the historical and current periods (Table 5.12).

The flow duration curves (Figure 5.3-Figure 5.5) further attest to the decrease in streamflow and show evidence of decreases in the annual flow rates from the historical period to the current period for all the catchments. Further investigation is to be done on the reasons for the decrease in the streamflow which may attribute the decrease in streamflow to human induced causes such as changes in land use and land cover. The short record length may also play a role, with a longer record length the natural variations in climate will be included and may result in the current record tending more towards the historical record curve.

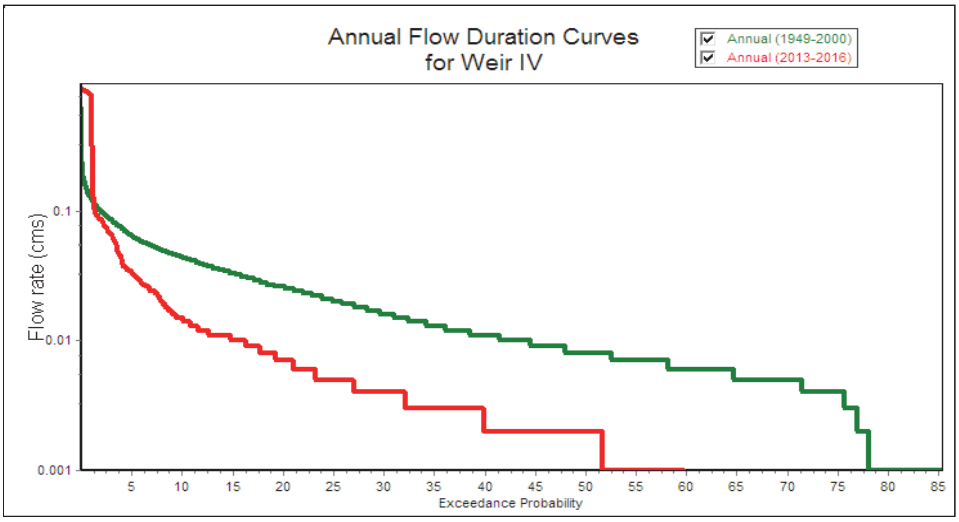

Figure 5.3: Annual flow duration curves for Catchment IV

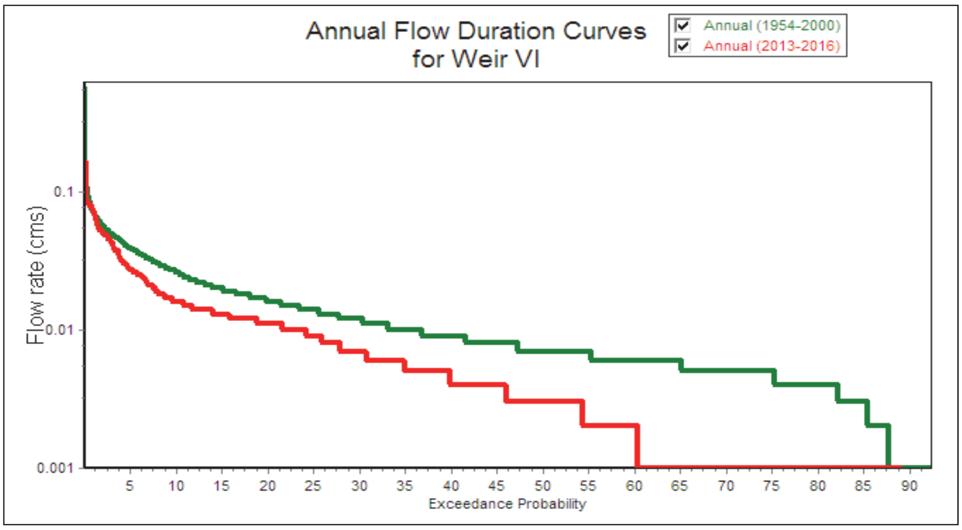

Figure 5.4: Annual flow duration curves for Catchment VI

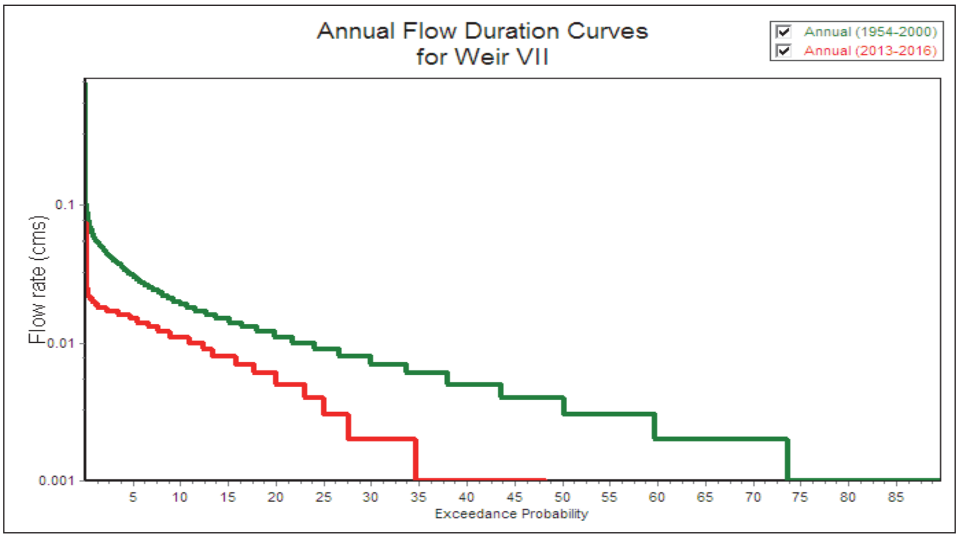

Figure 5.5: Annual flow duration curve for Catchment VII

6. IMPROVING THE UNDERSTANDING OF RAINFALL DISTRIBUTION AND CHARACTERISTICS ACROSS THE CATHEDRAL PEAK CATCHMENTS

6.1 Use of Geostatistics to Improve the Understanding of the Spatial Distribution of Rainfall

6.1.1 Introduction

The characterization of spatial and temporal rainfall variability, is essential for hydrological and ecological analyses (Tao, 2009, Aghakouchak *et al.*, 2011, Vogel *et al.*, 2012, Masson and Frei, 2014). Inherently, this variability is distinctly more apparent in mountainous areas compared to low lands (Cegnar, 2005, Thompson *et al.*, 2009, Chang *et al.*, 2014).This rainfall characteristic is mainly attributed to the interaction between atmospheric circulation and topographic features of the landscape, particularly altitudinal variation or orography (Prudhomme and Reed, 1998, Mair and Fares, 2010, Tan *et al.*, 2012, Roe, 2005). Orographic effects influence the local distribution and intensity of rainfall when forced upward movements of moisture filled air due to topographic barriers, result in more precipitation on the windward side and less precipitation on the leeward side (Chang *et al.*, 2014, Arora *et al.*, 2006, Houze Jr and Medina, 2005).

Despite the above understanding, however, a precise understanding of the spatial distribution of rainfall in mountainous areas is still hindered by the typically sparse raingauge networks at higher altitudes (Ranhao *et al.*, 2008, Masson and Frei, 2014, Roe, 2005). Generally, raingauge networks cover mainly valley and low lying areas where the weather generating systems and resultant spatial patterns of rainfall are different to those active at higher elevations (Prudhomme and Reed, 1998). In South Africa, Pegram *et al.* (2014), mentions both a decrease in the raingauge network as well as the lack of raingauges located at high altitudes.

Rainfall interpolation using data from a limited number of raingauges is one method that hydrologists use to derive the spatial distribution of precipitation in mountainous areas (Groisman *et al.*, 2005, Masson and Frei, 2014, Vogel *et al.*, 2012, Duethmann *et al.*, 2013, Jacquin and Soto-Sandoval, 2013). Numerous interpolation methods have been proposed to interpolate rainfall from raingauge observations (Guan *et al.*, 2005, Putthividhya and Tanaka). Several studies have reported that conventional techniques such as Thiessen polygon, Inverse Distance Weighting, Isoheytal methods and Splines are do not fully account for both climatological and spatio-statistical properties of rainfall fields (e.g. Prudhomme and Reed, 1998, Guan *et al.*, 2005, Vogel *et al.*, 2012). Nevertheless, improved computing facilities and development of robust methods especially geo-statistical based methods have the potential of increasing our understanding of rainfall characteristics in mountainous areas (Hengl *et al.*, 2007).

Geo-statistical methods such as Kriging, are capable and have been shown to produce better estimates than traditional interpolation approaches (Goovaerts, 2000, Mair and Fares, 2010, Meng *et al.*, 2013, Omran, 2012, Saffari *et al.*, 2009). Additionally, they also provide some measures of accuracy and certainty in the predictions (Ly *et al.*, 2013). Another advantage of geo-statistical methods is the use of auxiliary variables to improve rainfall estimates (Mair and Fares, 2010).

According to Ly *et al.* (2013) the use of multivariate geo-statistical methods has shown more accurate interpolations compared to deterministic interpolation methods. Geo-statistical methods (such as regression-kriging) for the estimation of rainfall are flexible, comprehensive, robust and free from serious bias (Hengl *et al.*, 2007). Regression Kriging is a spatial prediction method that combines a regression analysis of the dependent variable on auxiliary variables with the interpolation of the residuals from that regression (Hengl *et al.*, 2007). Regression kriging has been applied widely in various fields such as climatology (Bajat *et al.*, 2013, Tadić, 2010) soil science (Hengl *et al.*, 2004, Omuto and Vargas, 2015, Zhu and Lin, 2010) and species distribution modelling (Meng, 2006, Hengl *et al.*, 2009).

This work builds from previous work done by Schulze (1976) who used deterministic methods such as trend surface analysis for rainfall estimation in the Cathedral Peak catchments. Trend surfaces of long term annual precipitation and the use of the weighted average method for two short term precipitation events were analysed. With a longer data record now available, recent advancements in interpolation methods and the increasing pressure on water resources it is necessary to revise the rainfall estimation for the Cathedral Peak research catchments. The objective of this research was to ascertain if the use of contemporary geo-statistical interpolation methods provided any improved estimates and understanding of the rainfall distribution across the Cathedral Peak catchments in the Drakensberg escarpment region.

6.1.2 Methodology

Data and processing

Historical rainfall data was obtained for the raingauge network of the Cathedral Peak catchments (I-X). The data was obtained from various historical sources but this data is now available from the South African Environmental Observation Network (SAEON). The catchments are considered to have a fairly dense raingauge network (1 gauge per 0.352 km^2) (Schulze, 1976), with the highest density of raingauges in the eastern catchments (VIII-X). The dataset consisted of a time-series with hourly, daily, weekly and/or monthly rainfall totals at 24 stations during the 46 year research period stretching from August 1948 to March 1994. Various types of raingauges have been used in the catchments. Not all of the raingauges were active for the full 46 year period and during the monitoring period some raingauges were replaced raingauges that were suited to work automatically (Schulze, 1974). Although rainfall measurements were available in hourly and daily time steps for some raingauges, the shortest common recording period for all raingauges was monthly, hence data was analysed on a monthly basis for this study.

In order to exclude the most obvious errors from the Cathedral Peak historical rainfall dataset, quality control procedures included checking for the completeness of the dataset and the detection of outliers or physically impossible values as outlined by Einfalt and Michaelides (2008). Varying periods of records at individual gauges required the adjustment of rainfall to a standard base period. The 20 year period October 1965 to October 1985 was a period during which most gauges recorded simultaneously, thus it was chosen as the base period. Although the World Meteorological Organization (WMO) recommends the use of 30 year means, several authors (e.g. MarquíNez *et al.*, 2003, Arora *et al.*, 2006) have used shorter time periods for data analysis.

Five rainfall patching methods namely: “nearest neighbour by distance; nearest neighbour by correlation; inverse distance weighted; average of gauges selected by correlation and multiple linear regression analysis” were tried to infill the missing monthly rainfall data. The performance of all methods was compared using three error statistics namely Root Mean Square Error (RMSE), Mean Bias (MB) and a correlation coefficient (R^2). Of these, multiple linear regression had the least error based on the above error statistics evaluation and thus was used to infill gaps in the monthly rainfall data for 21 of the 24 gauges. The remaining three raingauges were excluded due to insufficient data lengths during the 20 year base period and also increased distance from the catchments.

Seasonal analysis

Analysis of the mean annual, wet and dry season rainfall confirmed a strong wet and dry season trend. On average, 83% of the annual rainfall occurs during the wet season (September to February) with the North facing gauges receiving the most rainfall during both wet and dry seasons (Table 6.1). Rainfall data for the area is strongly seasonal, therefore mean rainfall for both the dry season (March to August) and wet season (September to February) was calculated for further analysis. Based on previously considered auxiliary variables (altitude, longitude and latitude) for the area (Schulze, 1976) and a comprehensive literature review, it was therefore hypothesized that factors such as altitude (m.a.sl), slope angle, slope orientation (aspect), latitude and longitude could be used to predict rainfall for the ungauged sites.

Table 6.1: Topographic and seasonal distribution of average rainfall for raingauges in different aspects

			Rainfall (mm)			
Aspect	**Gauge**	**Altitude**	**Wet Season**	**Dry Season**	**Annual (1965-1985)**	**Annual (1950-1969)**
North	Ic	1846	1035	229	1241	1422
	IIa	2292	1254	284	1510	1738
	IIb	1974	1260	282	1515	1658
	IIc	1867	1182	262	1419	1508
	IIIa	2197	1176	270	1418	1573
	IVa	2134	1098	249	1095	1400
	VIIa	1986	984	225	1181	1357
	VIIb	1910	1087	232	1309	1356
	Mike’s Pass	1861	1045	237	1259	1259
East	IIIb	1973	1098	244	1317	1565
	VIIIc	1883	1095	249	1039	1261
	IXa	1969	960	225	1156	1280
	IXb	1903	905	232	1095	1284
South	IXc	1828	862	187	1030	1264
	Xa	2009	972	207	1157	1337
	Xc	1848	968	198	1145	1254
West	VIIc	1849	1050	237	1262	1405

Regression analysis

Regression analysis was used to determine if the considered predictor variables (altitude, aspect, latitude and longitude) showed any significance in explaining the variation in the annual, wet and dry season rainfall. Utilizing the above predictor variables as independent variables, and rainfall (annual, wet or dry period) as the dependent variables, the regression equation (Eq. 6.1) was used:

$$Y = \alpha + \beta_1 X_1, + \beta_2 X_2 + \ldots \beta_N X_n \qquad \text{Eq. 6.1}$$

Where:

Y = dependent variable (rainfall for annual, wet or dry period)

X_i = independent variable (altitude, aspect, latitude and longitude)

β = beta weights (slopes of each independent variable)

α = Y intercept.

Regression Kriging

Kriging is an interpolation method that uses values of a variable at known geographical locations to estimate values at unknown locations. Kriging relies on the fact that observations are not independent (Hengl *et al.*, 2007). Regression kriging is a type of kriging that uses secondary variables for more accurate predictions (Karl, 2010). The method uses multiple regressions to explain the relationship between the observed variable and the secondary variables considered. The regression and kriging results are combined to produce not only a prediction surface, but also an error surface. Regression Kriging is therefore essentially a spatial prediction method that combines regression of the dependent variable on auxiliary variables (altitude, aspect, latitude and longitude) with the interpolation of the residuals from that regression (Hengl *et al.*, 2007).

With fitted parameters of the regression model and of the residual variogram, regression kriging was used to derive rainfall predictions at all locations. All subset regression was used in regression kriging to select predictor variables with regression slopes statistically significant at a p level of < 0.05. The coefficient of determination (R^2) was used as a measure of the goodness of fit of the model. Additionally, the Akaike Information Criterion (AIC) which is a measure of the relative quality of a statistical model for a given dataset was also used to assess the predictive power of the developed model. The combination of both the regression and kriging methods are illustrated below (Eq. 6.2):

$$z = (s_o) = m(s_O) + \hat{e}(s_o)$$
$$= \sum_{k=0} \beta k \cdot qk(s_o) + \sum_{i=1} \lambda_i \cdot \hat{e}(s_i) \qquad \text{Eq. 6.2}$$

Where:

z = predicted value of the target variable at an unknown location

$m(s_0)$ is the fitted deterministic part,

$\hat{e}(s_0)$ is the interpolated residual,

β_k are the estimated regression model coefficients

λ_i are kriging weights determined by the spatial dependence structure of the residual and

$e(s_i)$ is the residual at location s_i.

6.1.3 Results

Predictor variables from regression analysis

The best predictor models were selected based on the criteria that the p value of each predictor variable be less than 0.05 and the AIC value the smallest. All subsets regressions (Tables 6.2-6.4) indicate that the overall best predictors of the distribution of rainfall for the annual, wet season and dry season respectively, are longitude and altitude. Longitude shows greater significance than altitude explaining 72% of the rainfall variability and altitude explaining 26% of the rainfall variability for MAP (Table 6.2), 73% and 26% for the wet season (Table 6.3) and 50% and 22% for the dry season (Table 6.3), respectively. The significant negative effect for the MAP (Table 6.2) and wet season (Table 6.3) indicates an increase in longitudinal direction (East-West) relates to an increase in rainfall. A small positive effect in the dry season (Table 6.3) indicates that there may be different rainfall variability patterns.

Table 6.2: Subset regressions for MAP

	P values						
Model	**MAP**						
	AIC	**R^2adj**	**Longitude**	**Latitude**	**Altitude**	**Aspect**	**Slope**
1 term	241.29	0.72	**8.40E-07**	-	-	-	-
	261.32	0.26	**-**	-	0.011	-	-
	263.41	0.18	**-**	-	-	0.03	-
2 terms	242.2	0.73	**1.65E-05**	-	0.178	-	-
	243.63	0.71	**6.90E-06**	-	-	-	0.43
	243.93	0.71	**4.85E-06**	0.541			
3 terms	245.41	0.72	**2.73E-05**	0.63	0.207	-	-
	245.62	0.71	**1.0E-04**	-	0.185	0.80	-
	245.67	0.71	**2.85E-05**	-	0.284	-	0.875
4 terms	249.29	0.70	**1.5E-04**	0.624	0.212	0.772	-
	249.4	0.70	**4.83E-05**	0.653	0.265	-	0.932
	249.6	0.70	**1.5E-0.4**	-	0.306	0.821	0.914

The high R^2 and small AIC values for longitude alone indicate that the overall distribution is strongly directional with an east west directional gradient. The combination of both longitude and altitude had a larger R^2 of 0.73, 0.74 and 0.51 for the annual, wet season and dry season, respectively. However, when combined with longitude, altitude had a significant influence for all periods ($p < 0.05$). Aspect alone showed to be significant for the annual and dry seasons, explaining 18% and 19% of the rainfall variability, respectively. The three subset model of longitude, altitude and aspect indicated a slight decrease in R^2 with altitude and aspect being insignificant for all rainfall periods. Although there are latitudinal differences in the station positions, latitude is found to play no significant role in influencing the rainfall distribution for the area and neither does slope. The regression analysis reveals that based on the R^2 values and small AIC values, a simple linear regression with longitude alone, altitude alone or the combination of both longitude and altitude can be used to satisfactorily characterize the rainfall variability for the Cathedral Peak area. Regression models selected for each rainfall period are shown in Table 6.4.

Table 6.3: Subset regressions for the wet season and dry season

	P values													
Model	**Wet Season**							**Dry Season**						
	AIC	**R^2_{adj}**	**Long.**	**Lat.**	**Altitude**	**Aspect**	**Slope**	**AIC**	**R^2_{adj}**	**Long.**	**Lat.**	**Altitude**	**Aspect**	**Slope**
1 term	231.91	0.73	**5.23E-07**	-	-	-	-	187.52	0.50	**1.9E-04**	-	-	-	-
	253.08	0.26	-	-	0.011	-	-	196.98	0.22	-	-	0.019	-	-
	255.29	0.17	-	-	-	0.659	-	197.66	0.19	-	-	-	0.027	-
2 terms	232.93	0.74	**1.05E-05**	-	0.189	-		188.98	0.51	**0.002**	-	0.245	-	-
	234.23	0.72	**4.44E-06**	-	-	-	0.422	190.19	0.48	**0.001**	-	-	-	0.554
	234.36	0.72	**3.18E-06**	0.465	-	-	-	190.30	0.48	**0.003**	-	-	0.616	-
3 terms	236.23	0.73	**1.20E-05**	-	0.136	0.332	-	190.77	0.50	**0.002**	0.246	0.105	-	-
	236.33	0.73	**1.86E-05**	0.781	0.273	-	-	192.26	0.49	**0.013**	-	0.271	0.680	-
	236.41	0.73	**1.88E-05**	-	0.310	-	0.913	192.39	0.49	**0.013**	-	0.271	-	0.680
4 terms	240.10	0.71	**2.10E-05**	0.671	0.189	0.319	-	194.63	0.50	**0.012**	0.271	0.125	0.745	-
	240.23	0.71	**2.20E-05**	-	0.242	0.345	0.894	194.76	0.50	**0.003**	0.272	0.153	-	0.923
	240.33	0.71	**3.37E-05**	0.798	0.335	-	0.946	196.11	0.46	**0.016**	-	0.312	0.648	0.736

Table 6.4: Selected regression models for the annual, wet season and dry season

Period	**Equation**	**F value**	**R^2**
Annual	=477.37-139.9 longitude + 0.276 x Altitude	27.04	0.73
Wet Season	=476.88-139.8 longitude + 0.258 x Altitude	28.70	0.74
Dry Season	=442.2-130.19 longitude + 0.359 x Altitude	11.20	0.50

Rainfall spatial variability estimation from kriging

The annual, wet season and dry season rainfall data suggested higher autocorrelation in a west to east direction compared to a north-south direction. Semivariogram models were therefore chosen based on its ability to depict the anisotropic behaviour of the target variables. Both manual and automatic methods of fitting the semivariogram models were used. Empirical model variograms (Spherical, Gaussian, exponential and circular models) were visually compared to the automated fitted models. Residual semivariograms were then derived based on the semivariograms of the target variables. The Gaussian empirical models were selected to model the covariance structure of both the target variables and the regression residuals.

The rainfall patterns for the long term mean annual data shows an overall strong directional distribution ranging from over 1531 mm p.a. in the north and south west to under 1020 mm in the East (Figure 6.1). The influence of altitude appears significant in the spatial patterns of rainfall only in the two steepest catchments (namely, II and III). A similar pattern is observed for the wet season

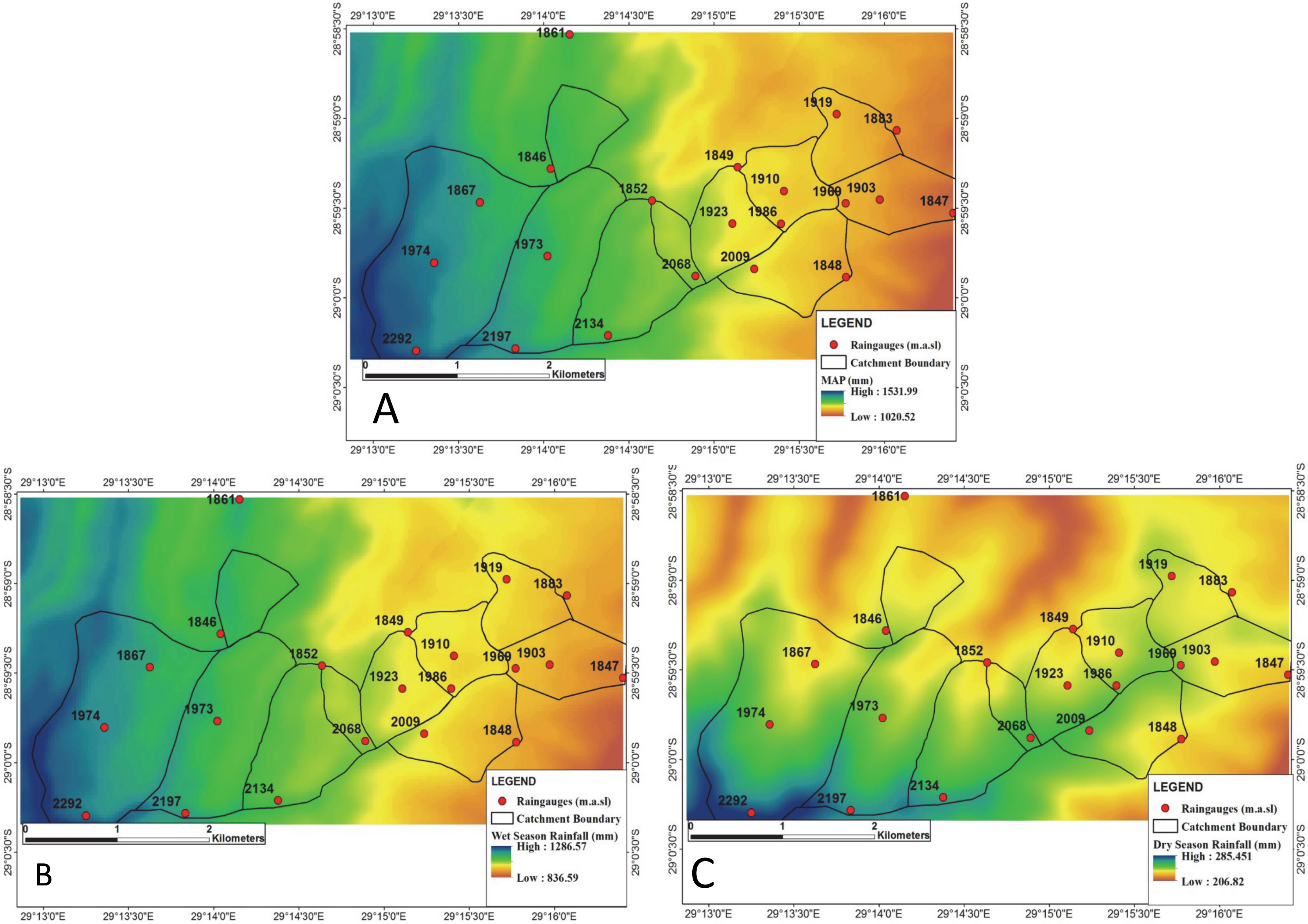

Figure 6.1: a) Long term mean annual, b) wet season and c) dry season rainfall distribution pattern

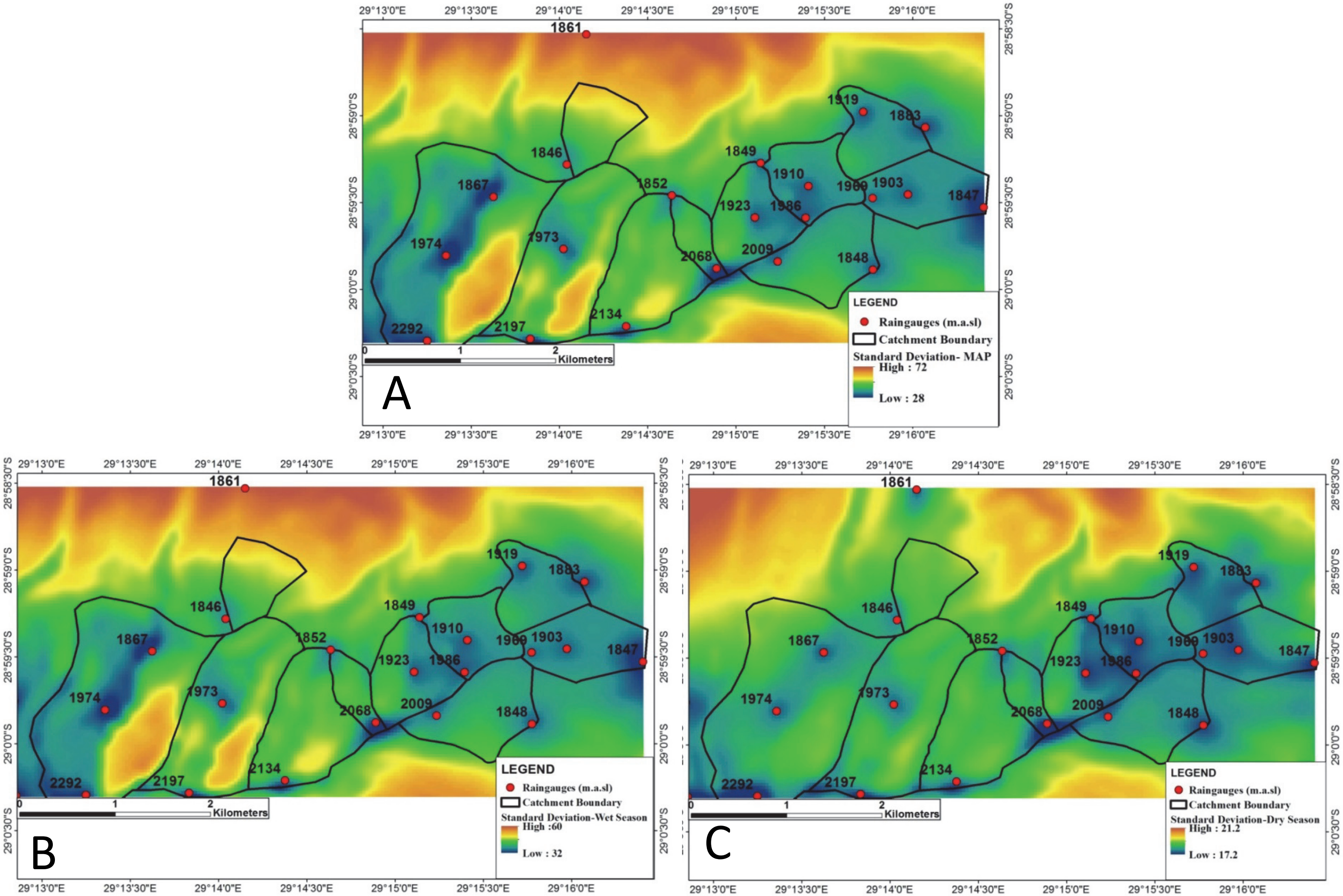

Figure 6.2: a) Long term mean annual, b) wet season and c) dry season rainfall standard deviation distribution patterns

where the rainfall amounts range from over 1286 mm p.a. in the North to South West to under 836 mm in the East. A distinct pattern is observed during the dry season where rainfall ranges from 285 mm in the North west to approximately 240 mm in the east and under 206 mm in the South east (Figure 6.1). The rainfall distribution during the dry season indicates the typical west to east frontal movement over South Africa where the South facing slopes receive less rainfall than the north facing slopes.

Cross validation and error analysis

Unlike when using deterministic interpolation methods, use of regression kriging allows that with each prediction map generated, a prediction error or standard deviation map is generated using the same kriging method. Prediction error maps of standard deviations were used to assess the accuracy of the predicted rainfall maps. Standard deviations for the wet season have the same pattern as the MAP, however, lower standard deviations in areas with few raingauges were observed (Figure 6.2). The lowest standard deviations were observed for the dry season especially in the North West and East.

Cross validation results indicated a high Root Mean Square Errors (RMSE) for the MAP and wet season of 163.89 and 137.62 respectively, and a low RMSE for the dry season. Plots of observed and predicted rainfall indicated high R^2 for the MAP and wet season (78% and 79.7% respectively) and low R^2 (55%) values for the dry season (Figure 6.3). The consideration of more frontal related variables for the dry season such as wind and distance to sea may assist in better characterization of the rainfall variability

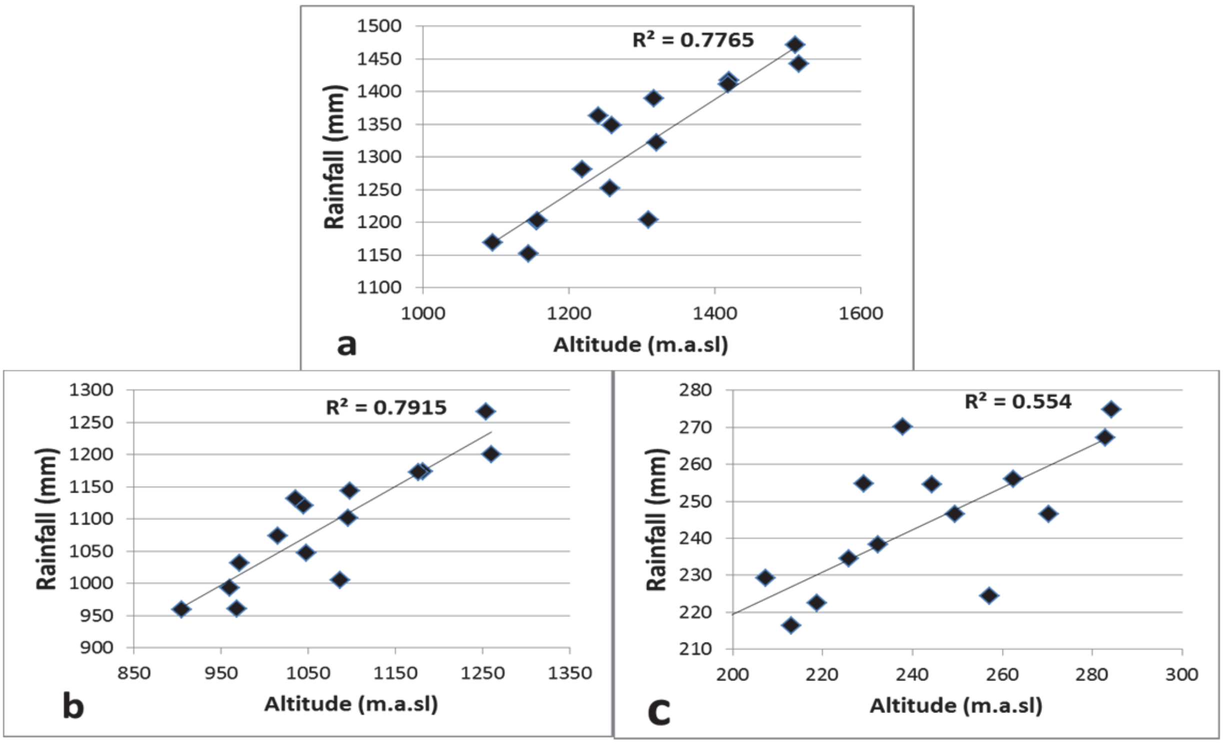

Figure 6.3: Plots of predicted vs observed for the a) annual, b) wet season and c) dry season using Regression Kriging

6.1.4 Conclusion

The Regression kriging method showed to be a useful tool in characterizing the rainfall distribution for the Cathedral Peak catchments. The method was able to use auxiliary information available in the form of maps of covariates (altitude, longitude, aspect and slope) to explain variations in rainfall for the area as well as provide prediction errors. Predictions indicated that the overall rainfall distribution for the area is strongly directional particularly for the long term mean annual rainfall and for the wet season, as well as a significant effect on rainfall distribution due to altitude. The results are comparable to what was obtained by Schulze (1976). The main differences between the methods used however were that Schulze (1976) used more variables and the deterministic interpolation method did not allow for the production of error maps compared to the regression kriging technique. Results by Nel and Sumner (2006) and Nel and Sumner (2007) were also comparative to results from this study indicating the role of altitude in characterizing rainfall for catchments and the insignificance of the positions of the raingauges (latitude) compared to eastward distance from the escarpment.

Comparatively, lower rainfall amounts were predicted for all rainfall periods in this study with different rainfall patterns observed in the dry season. Rainfall estimates were lower by approximately 260 mm in the South West and approximately 220 mm in the East as compared to the rainfall surfaces produced by Schulze (1976). This may be attributable to the different record period used in the Schulze (1976) study (1950-1969), as well as the higher long term means compared to this study. The major rainfall producing systems are attributed to large scale line thunderstorms and orographically induced thunderstorms in summer (Nel and Sumner, 2007) which are driven inland from an easterly direction, while approximately 43 mid latitude cold fronts each year originating from the western Atlantic move across South Africa in a west to east direction resulting in winter rainfall (Grab and Simpson, 2000, Nel, 2008).

Estimations clearly represented the spatial distribution of rainfall for the annual and wet season from east to west as well as the west-north-east to east south east spatial distribution for the dry season. According to Houze (2012) convective systems are enhanced by upslope flow and therefore higher rainfall is observed in the two steepest catchments during the annual and wet season. Convective systems moving in from the east are therefore enhanced in the high altitude catchments. In the dry season, frontal systems on the other hand may rise easily over the terrain resulting in maximum rainfall on ridges and minimum in valleys (Houze, 2012). This spatial pattern is observed for the dry season where the top of the catchments receive higher rainfall than the valleys in the catchments dissected by deep ravines. These assumptions are however inconclusive considering the size of these precipitating mechanisms relative to the size of the catchments overall.

Longitude and altitude were shown to have lower significances in explaining the dry season rainfall variability which may be due to the different effect of topography on frontal systems compared to the effect on convective rainfall. However, the use of long term means to characterize rainfall for an area which receives predominantly sub daily short duration events is not fully representative of the nature of rainfall in the area and can also explain the high RMSEs. Both a temporal and spatial analysis of rain event properties for the area will allow for better understandings and characterisations of the type and distribution of rainfall received in the area. Areas of high prediction error were related to areas with fewer raingauges. Overall, the implications of the findings of the study at Cathedral Peak indicate that with improved computing facilities and the recent advancements in interpolation methods has allowed easier methods for satisfactorily characterizing rainfall variability for the area with the least amount of variables.

6.2 Use of Rain Event Properties to Improve the Understanding of the Spatial Distribution of Rainfall

6.2.1 Introduction

At both spatio-temporal scales, the assessment of rain event properties is of crucial importance for hydrological and climate studies (Nel, 2008; Haile *et al*., 2011; Ruan *et al*., 2014; Dunkerley, 2008a; Dunkerley, 2008b). Rain event properties such as rain rate, rain event depth, event duration, inter-event time (IET) as well as daily rainfall totals and number of rain days are important in hydrological studies (Haile *et al*., 2011). Such hydrological studies may include studies of rainfall erosivity (Nel *et al*., 2010; Meusburger *et al*., 2012) runoff generation (Wenninger *et al*., 2008; Bangira, 2013; Masson and Frei, 2014; Mul *et al*., 2009), interception losses (Bulcock and Jewitt, 2012; Zeng *et al*., 2000) and rainfall modelling (Prudhomme and Reed, 1998; Haile *et al*., 2011). Several studies (e.g. Kundzewicz *et al*., 2008; Arnell, 2011; Gosling *et al*., 2011) have shown that a change in atmospheric composition will result in the intensification of the hydrological cycle. Given the above, other scholars (e.g. Connolly *et al*., 1998; Prudhomme and Reed, 1998; Dunkerley, 2008b; Gupta and Waymire, 1993; Segond *et al*., 2006) suggested that it is imperative to examine statistical properties of rainfall events for trends towards an increasing frequency of extreme events as is predicted in climate change theory (Yilmaz, *et al*., 2014; Trenberth, 2011).

Rainfall characteristics of mountainous areas have been found to be characteristically more variable than that of low lands due to the interaction between atmospheric circulation and topography (Prudhomme and Reed, 1998; Roe, 2005; Mair and Fares, 2010; Tan *et al*., 2012). Orographic effects influence the local distribution and intensity of rainfall resulting in daily precipitation that may be localized in character (Sumner *et al*., 1995; Arora *et al*., 2006). According to Konrad II (1996) different rain event types are influenced by topography in different ways. Haile *et al*. (2011) showed that rain event properties can provide a better understanding of the link between rain producing mechanisms and the observed rainfall distribution in mountainous areas.

The Ukuhlamba Drakensberg area constitutes one of South Africa's most important watersheds (Sycholt, 2002; Briggs, 2008).The most in depth studies on rainfall properties of the KwaZulu-Natal Drakensberg area were conducted by Nel *et al*. (2010) and Nel and Sumner (2005; 2007; 2008), as part of ongoing long term meteorological monitoring in the mountainous regions of the KwaZulu-Natal Drakensberg. Results from Nel and Sumner (2008) showed lower rainfall depths from individual rain events on the escarpment compared to stations at lower altitudes. Nevertheless, they also found a slight increase in the number of rain days and rain events with increasing altitude.

A total of 26 raingauges were maintained within and across the catchments during the period October 1968-September 1971 with the first precipitation measurements from the Meteorological Site in 1948 (Schulze, 1974). An overall raingauge density of one gauge per 0.352 km² exists with the highest density of raingauges in the eastern catchments (Schulze, 1974). Thus far, a detailed analysis of rain event properties in the Cathedral Peak area is lacking apart from Schulze (1976) who focused on the estimation of both long and short term precipitation. Schulze (1976) estimated point and catchment precipitation for individual storms using trend surface analysis for 3 rain events but found results to be too coarse spatially. In addition, short term rainfall patterns were not found to follow directional and altitudinal trends due to the inherent local nature (Schulze, 1976). This calls for an improved understanding through an estimation method that accounts for the conditional variance of individual rain events in the Cathedral Peak area such as can be offered by using quantile regression.

When using ordinary least squares regression the relationship between the predictors and all parts of the conditional distribution of the dependent variable are often not fully explored (Lijun and Zhe, 2015). However, quantile regression allows for different subsets of predictors to be used for different parts (quantiles) of the conditional distribution of the dependent variable (Cade and Noon, 2003; Mcmillen, 2012; Wigena and Djuraidah, 2014). Additionally, no assumptions are made about the distribution (Hao and Naiman, 2007; Dunkerley, 2008a; Wigena and Djuraidah, 2014). Quantile regression has been used extensively in rainfall studies (e.g. Friederichs and Hense, 2007; Tareghian and Rasmussen, 2013; Wigena and Djuraidah, 2014; Lijun and Zhe, 2015). For example, Friederichs and Hense (2007) employed quantile regression in statistical downscaling of precipitation instead of using the traditional linear regression models to determine the conditional distribution of precipitation for any given day. Similarly, Lijun and Zhe (2015) used quantile regression to detect relationships between large scale atmospheric predictors and all parts of the distribution of rain events over Northern China. Their findings indicate that the impact of the large scale predictors on the daily precipitation becomes stronger with higher quantiles, whereas their impact on light precipitation is negligible. Frei (2012) used quantile regression for probabilistic forecasts of precipitation and scholars such as López López *et al* (2014), Weerts *et al* (2011), Mazvimavi (2010), Shiau and Huang (2014) and Dogulu *et al*., 2014 have used quantile regression for uncertainty analysis in hydrological forecasts and in climate change analysis.

This study aimed at evaluating rain event properties that could be used to characterize rainfall for mountainous areas such as the Cathedral Peak area. Quantile regression was used to examine the relationship between all parts of the distribution for different rain event categories with different predictor variables, towards the improved understanding of rainfall characteristics for the Cathedral Peak catchments

6.2.2 Methodology

Data collection

Rainfall data was collected from 23 rainfall stations in the Cathedral Peak area. For each of the 23 rainfall stations the following rain event properties: mean event rain rates, rain event depth, rain event duration as well as daily rainfall totals and the number of rain days were calculated. Quantile regression was then used to examine the relationship between all parts of the rainfall distribution for different rain event depths with different predictor variables (altitude, longitude, aspect and slope). Given that the rain event characteristics were required, only the data collected during the current monitoring period could be used and not the former monthly data.

Davis-MC Systems (D-MCS) automated tipping-bucket raingauges were installed in Catchments I, II, III, VIII, IX and X by the University of KwaZulu-Natal research team. While high intensity Texas TE525-series tipping bucket raingauges were installed in Catchments IV, V, VI and VII by the South African Environmental Observation Network (SAEON). An additional rain gauge was installed outside the catchments at a lower altitude to provide a better altitudinal cross-section. Prior to installation, an intensive re-calibration of the 14 D-MCS automated tipping-bucket raingauges was carried out after a 32% volume difference between each bucket compartment was revealed during initial tests. Re-calibration was done using two Campbell re-calibration methods (Campbell Scientific, 2005). The D-MCS automated tipping-bucket raingauges have a 163 mm collection diameter and were connected to a Hobo data logger (Onset, Bourne, England) which recorded rainfall on an event basis, with a tipping resolution of 0.2 mm. The Texas tipping bucket raingauges with a 152.4 mm diameter funnel were also connected to a Hobo data logger (Onset, Bourne, England) which recorded rainfall on an event basis, with a tipping resolution of 0.254 mm.

The concurrent recording period used in this study for all raingauges, spanned one year from 2 December 2013 to 2 December 2014. The D-MCS automated tipping bucket raingauges deem comparable records to the Texas high intensity automated tipping bucket raingauges. Gaps in the data were due to technical issues (e.g. logger failure) as well as periods during which raingauges had to be removed for controlled burning of the catchments.

Daily rainfall and rain event properties

For the purposes of this study, a rainday was defined as one in which at least 0.5 mm of rainfall is recorded. This definition is as used by Schulze (1976) and Nel and Sumner (2008). Rainfall data for each raingauge was analysed for the concurrent period 02/12/2013 to 02/12/2014 to determine the total daily rainfall and the total number of rain days for the entire period, wet season and dry season.

Additionally, rain event depth, event duration and mean event rain rate were analysed. The defined length for a dry period between two consecutive rain events i.e. inter-event time (IET), was selected as more than two hours. A rain event for this study is therefore described as a discrete event that generates more than 0.5 mm of rain and with an IET of more than two hours. The event depth was derived using the following formula:

$$\mathrm{de} = \sum_{\mathrm{i}=1}^{\mathrm{T_e}} \mathrm{I_i} \qquad \text{Eq. 6.3}$$

Where $\mathrm{d_e}$ is event depth; $\mathrm{T_e}$ is the event duration while I_i is the 1-minute rainfall depth at the i^{th} minute during a rain event since the start time of the rain event. Mean rain rate ($\mathrm{R_e}$) refers to the total rain event depth defined by the event duration to express mean conditions during the rain event, given by Equation 6.4 below:

$$R_e = \frac{d_e}{T_e} \qquad \text{Eq. 6.4}$$

Where, R_e is the mean rain rate; and d_e and T_e are as in Equation 6.3 above. The subset 'e' indicates that the calculation is based on the depth and duration of an event and is not based on time integrations such as 5 minutes, 13 minutes or 30 minutes. This distinguishes the difference between rainfall intensity (I) and mean rain rate (R_e). Mean rain rates are used to avoid reporting extremely high rain rates in very short time intervals. There are several classifications of rain rates in literature which reflect the regional variation in rainfall climate (Dunkerley, 2008b). In order to develop useful categories for rainfall intensity, event frequencies were compiled for a series of different intensity categories.

Preliminary correlation analysis was undertaken to identify the ranges of mean rain rates that showed common relationships with the topographic variables. Using the preliminary correlations as a guide, mean rain rates were categorised into the following groups: light (<1 mm/h); moderate (1mm/h < R<10 mm/h); and heavy (10 mm/h < R <15 mm/h).

Interpolation technique

The spline interpolation technique was used to produce surface maps of both daily and sub-daily rainfall properties for the Cathedral Peak catchments. The spline interpolation method produces a prediction surface that uses mathematical functions to pass through the sampled points by reducing the total surface curvature (Azpurua and Ramos, 2010). An advantage of this technique is that the splining functions are able to generate sufficiently accurate surfaces from a small sample size and retain small features (Azpurua and Ramos, 2010). The regularized method in Arc GIS 10.2.2 was used in this analysis for the use of a small sample size and values that may lie outside the sample data range to produce a smooth surface.

Quantile Regression

Quantile Regression (QR) is an extension to the conventional linear regression (Koenker, 2005). The "quantreg" package add-on to the R language (http://www.r-project.org/) was used for quantile regression analysis in this study. A brief description of the method is given below. Contrary to the conventional linear regression, QR allows the estimation of any or all conditional quantiles of a response variable distribution instead of focusing on averages. This allows a more accurate view of all possible relationships between the response variable and considered explanatory variables. The formula is given below:

Let Y denote the response variable, rainfall in this case, and X a vector of the considered explanatory variables. For any given quantile τ the linear QR can be described as Y= "f ' (" α_τ,β_τ,x), with β_τ denoting the QR coefficient and ατ the intercept for each τ. A more detailed description of QR method is given in Koenker, 2005 and Lijun and Zhe (2015).

6.2.3 Results

Daily rainfall characteristics

Full datasets were collected at most raingauge sites with data loss at Mikes Pass (10.8%), IIA (9.14%), IIB (18.9%), IIIA (4.1%), IVA (10.8%), IVB (10.8%), IVC (16.6%), VIB (6.3%), VIIA (6.3%) and VIIB (4.6%). For the concurrent record period 02/12/2013 to 02/12/2014, the spatial variation in the total daily rainfall and total number of raindays was analysed. In terms of altitude, raingauge IIC at an altitude of 1867 m.a.sl recorded the highest rainfall total for the concurrent period (1419 mm) and for the wet season (1166 mm) over 143 and 115 raindays respectively. Similarly, raingauge IC and the Met station at low altitudes (1846 m.a.sl and 1861 m.a.sl) recorded high rainfall totals (1232 mm and 1297 mm) in a high total number of raindays (133 and 131). Comparatively, the two high altitude raingauges above 2000 m.a.sl (VA and XC) recorded 493 mm and 440 mm less than raingauge IIC, with 19 and 33 fewer raindays respectively. Analysis showed that in general low altitude raingauges received higher rainfall totals in a higher total number of rain days than high altitude raingauges. Additionally, as the total daily rainfall decreases from west to east, so does the total number of raindays (Figure 6.4 and Figure 6.5).

With respect to both aspect and altitude, the two steepest catchments received higher total daily rainfall and number of rain days than raingauges in the east. Within the two steepest catchments however, the low altitude raingauges (IIC and IIIB) received higher total daily rainfall compared to the high altitude raingauges IIA and IIIA. A similar spatial pattern is observed in the total number of raindays for the dry season where the low altitude raingauges measured a higher number of raindays than the high altitude raingauges. A slightly different spatial pattern is observed between the total number of rain days in the annual and wet season, where high altitude raingauges measured a higher number of raindays. An overall decrease in the number of raindays is observed from west to east for all periods (Figure 6.6).

Rain event properties

Rain event properties were analysed for rainfall records for the concurrent period 02/12/2013 to 02/12/2014. Descriptive statistics of rain event depth, event duration and mean event rain rates (Table 6.5), showed that the largest number (151) of rain events was recorded at raingauge IIC while the lowest number (132) of rain events was recorded at raingauge VIIIa. Raingauge IXB recorded the highest maximum event depth of 108.20 mm which can be considered an extreme event since it is approximately 29 times higher than the median of the observed events.

In terms of event duration raingauge VIB recorded the longest single event lasting over two and a half days (54.53 hours) and raingauge IXC recorded the shortest event duration of 2.4 minutes. Mean event rain rates ranged between 0.13 mm/hr and 41.6 mm/hr. Raingauge VIB recorded the highest mean rain rate of 41.6 mm/hr for the considered raingauges, with a rain depth of 9 mm recorded in 13.2 minutes. The lowest mean event rain rates of 0.13 mm/hr were recorded at raingauges IIIB and IIC. In terms of altitude, lower altitude raingauges showed a slight indication of higher rain rates compared to higher altitude raingauges.

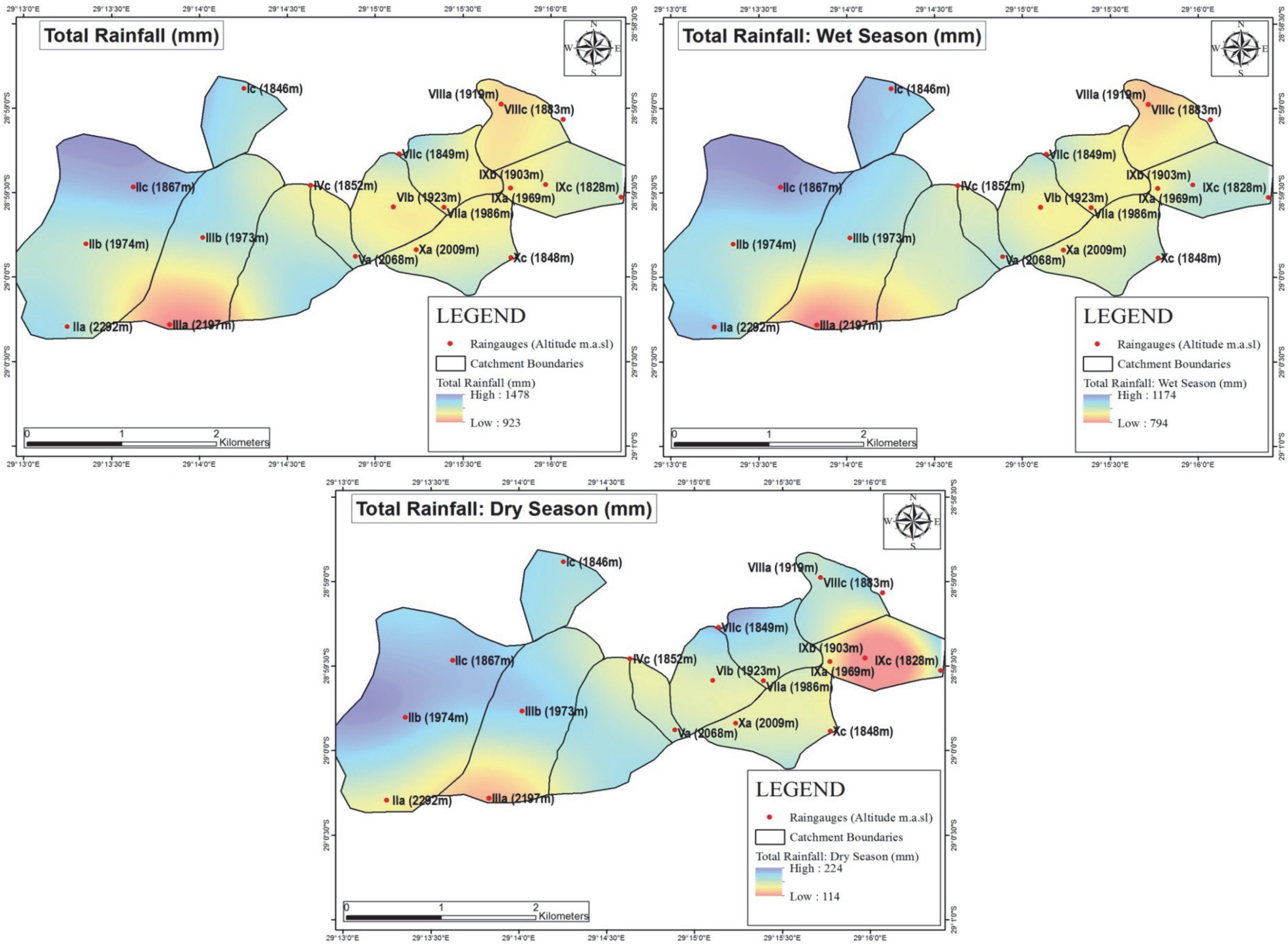

Figure 6.4: Estimated total daily rainfall for the Cathedral Peak catchments

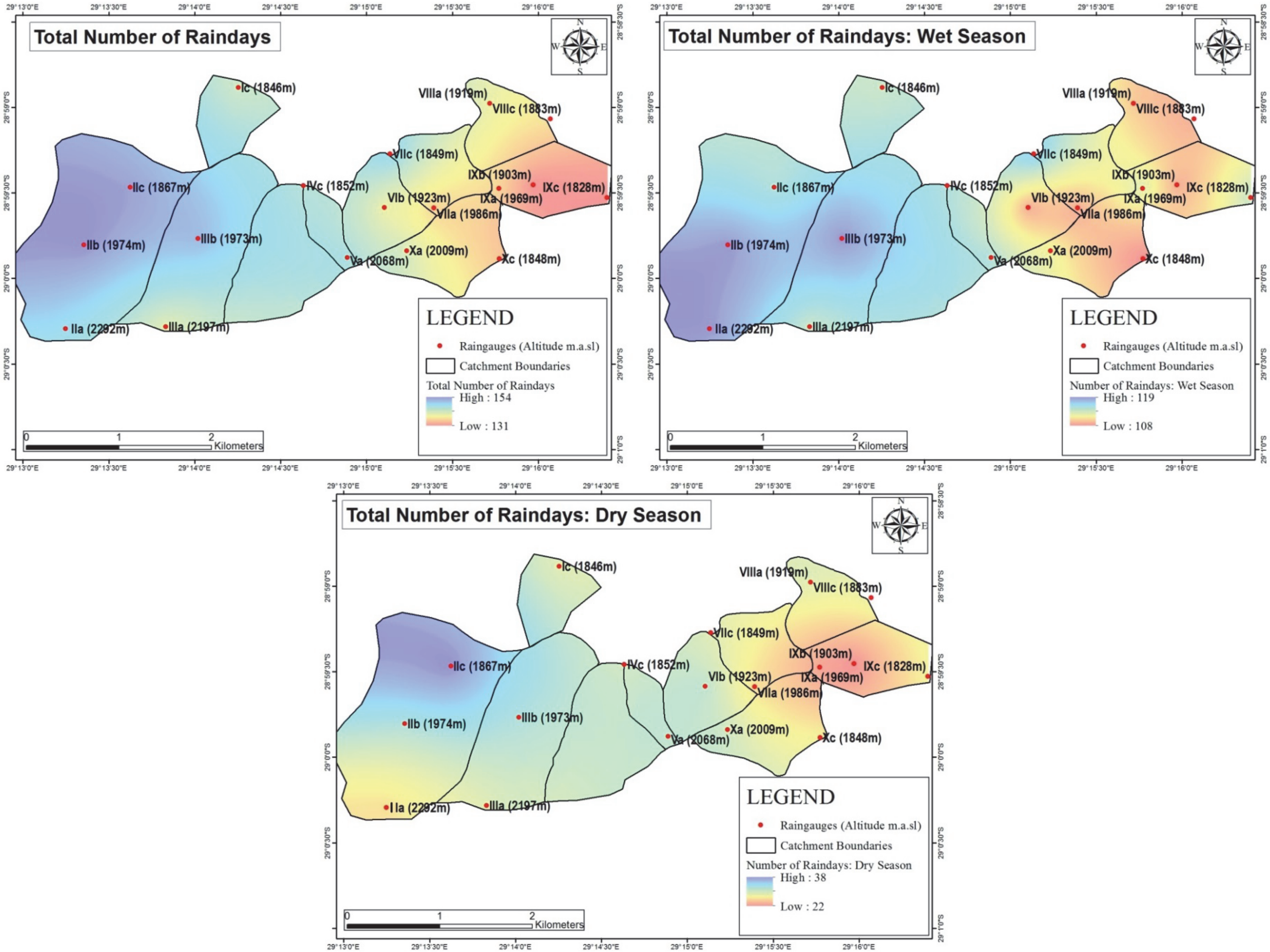

Figure 6.5: Estimated total number of raindays for the Cathedral Peak catchments

Table 6.5: Summary of rain event properties for all the raingauges in the Cathedral Peak catchments

			Depth (mm)			Duration (hours)			Event Rain Rate (mm/h)		
Station	**Altitude**	**Total No. of events**	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**
Mikes Pass	1861	112	0.60	6.99	55.00	0.04	5.22	16.08	0.14	1.63	17.91
Office Station	1556	147	0.51	16.49	78.00	0.05	6.04	35.00	0.16	2.52	28.96
IC	1846	138	0.60	8.78	72.40	0.12	5.53	23.00	0.10	2.99	37.50
IIA	2292	138	0.60	8.79	70.00	0.10	5.97	22.90	0.20	2.96	37.30
IIB	1974	145	0.60	8.52	44.20	0.11	5.85	42.10	0.20	2.50	18.20
IIC	1867	151	0.60	10.13	80.40	0.13	6.91	34.10	0.10	1.99	24.30
IIIA	2197	138	0.60	5.99	46.60	0.13	5.26	42.10	0.10	1.98	20.00
IIIB	1973	143	0.60	7.95	56.00	0.12	5.87	39.80	0.10	2.27	18.10
IVC	1852	138	0.50	8.49	82.00	0.25	4.92	23.90	0.10	2.39	30.50
VA	2068	136	0.50	7.85	71.60	0.11	4.71	27.10	0.20	2.74	27.20
VIB	1923	136	0.50	6.36	42.90	0.11	5.48	54.50	0.20	2.56	41.60
VIIC	1849	137	0.50	8.28	73.90	0.11	4.58	25.00	0.20	2.97	32.20
VIIIA	1919	132	0.60	7.90	68.00	0.21	5.00	25.80	0.20	2.26	17.80
VIIIC	1883	141	0.60	7.48	88.20	0.18	4.75	27.40	0.20	2.19	27.40
IXA	1969	138	0.60	7.41	54.60	0.10	4.89	35.20	0.20	2.62	25.10
IXB	1903	139	0.50	9.71	108.20	0.11	4.67	31.70	0.20	3.12	31.80
IXC	1828	137	0.60	8.19	89.00	0.04	4.78	20.90	0.20	3.09	40.00
XA	2009	140	0.60	7.43	63.40	0.14	5.15	23.70	0.20	2.37	23.80
XC	1848	137	0.60	8.03	61.40	0.11	4.79	28.30	0.20	2.78	36.30
Note: Rain event duration calculated in fractions of an hour											

The medians of rain event properties were interpolated using the spline interpolation method to produce prediction surfaces for the Cathedral Peak catchments shown in Figure 6.6. Analysis indicated an overall decrease in the median rain event depth and median event durations from west to east. An indication of generally lower median rain event depths and higher rain event durations for higher altitude raingauges is observed with lower altitude raingauges measuring higher median rain event depths over shorter event durations. No clear spatial pattern is observed for the rain rates however on average, low altitude raingauges showed a slightly higher correlation with rain rates.

The influence of altitude and slope for both the Ordinary Least Squares (OLS) regression and QR are similar, indicating that the use of linear regression in understanding and predicting rainfall for the area is viable. However, there are differences in the influence of aspect and longitude shown by QR compared to the OLS regression. While OLS regression showed that aspect has an insignificant effect on rain event depths, QR showed a statistically significant influence by aspect on both low and high rain event depths.

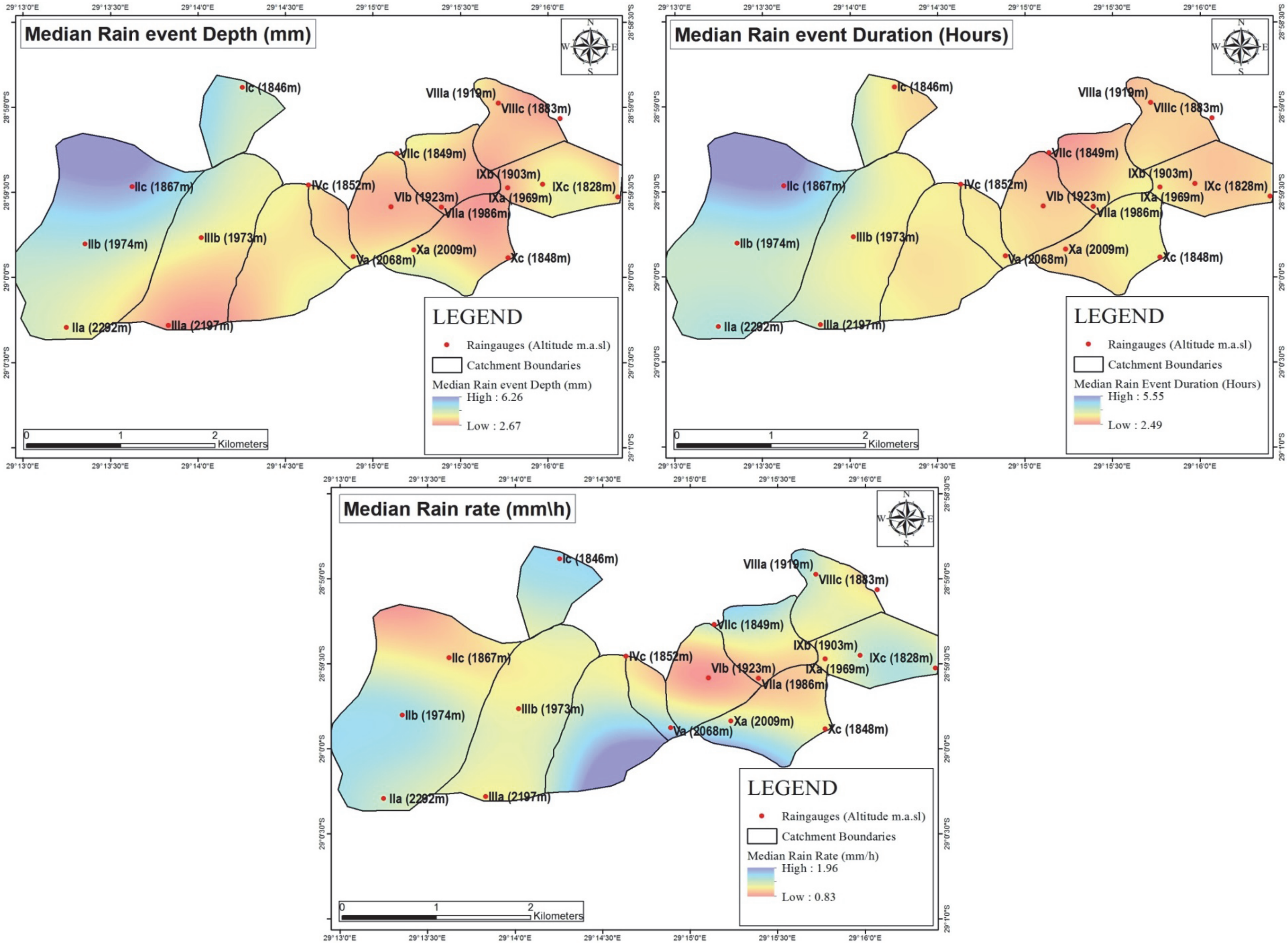

Figure 6.6: Estimated median rain event properties for the Cathedral Peak catchments

Additionally, the positive influence of aspect is more pronounced in the higher quantiles (0.70, 0.80, 0.90) with lower decreasing levels of uncertainty, although the influence is small. This indicates that there is a slight influence of aspect on high rain event depths for high slope angles although the relationship is weak. While OLS regression shows a negative relationship between longitude and the conditional distribution, QR shows a positive relationship in the lower quantiles with slope values of 50 although the confidence envelopes cross the zero line (Figure 6.7) indicating no statistically significant relationship. This indicates a possibility of different directional influences for low and high rain event totals and may give more insight into the winter and summer weather systems and their direction of travel over the Cathedral Peak catchments.

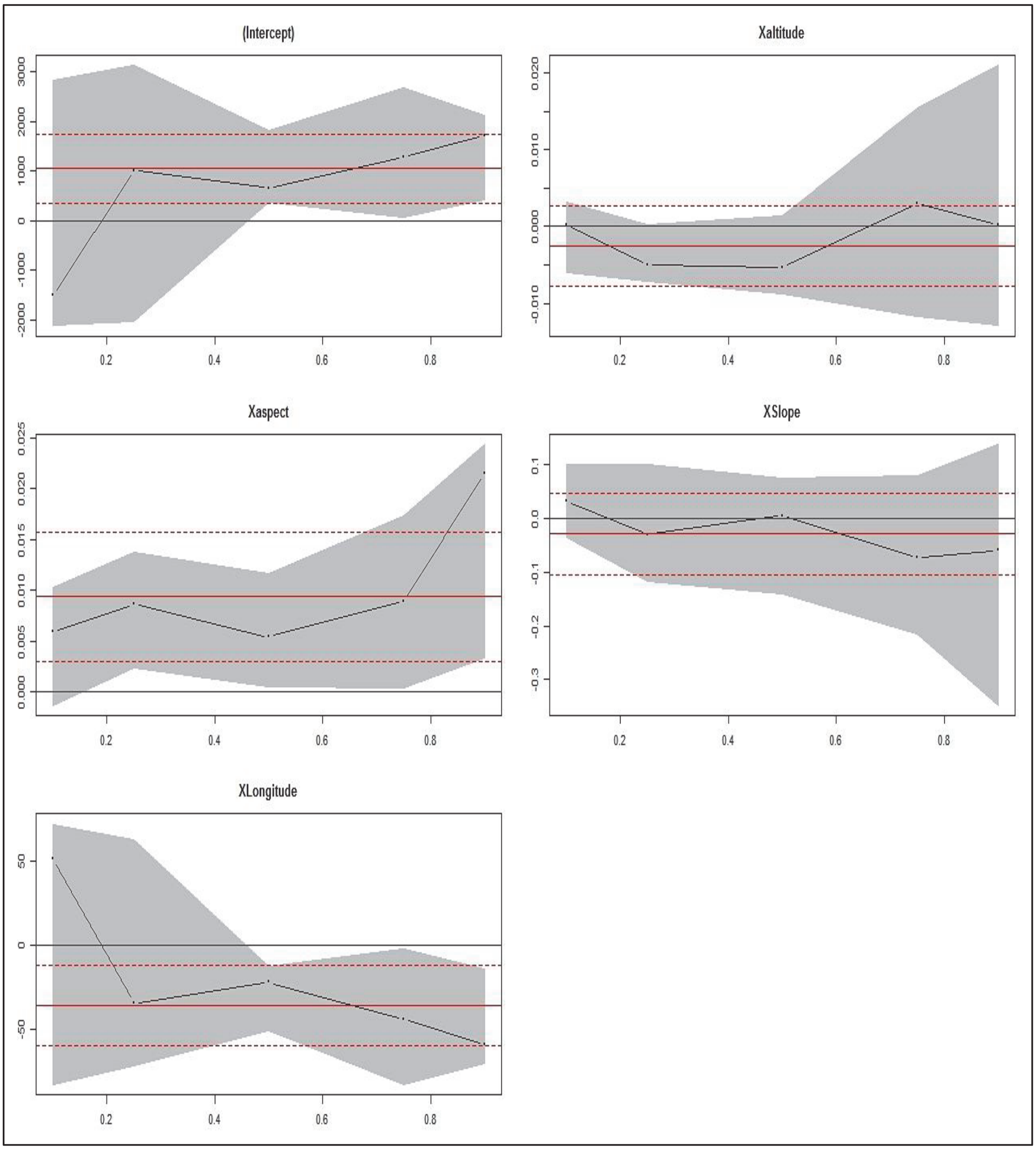

Figure 6.7: Relationship between rain event totals and predictor variables of altitude aspect slope and longitude. Coefficients of Quantile regression (black dashed lines) and Ordinary Least Squares (OLS) regression (solid red lines) using quantiles of rain event

6.2.4 Conclusion

The objective of this study was to improve the understanding of the spatial distribution of rainfall in the Cathedral Peak catchments by analysing properties of daily rainfall, rain events and to evaluate how different rain event depths are affected by selected rainfall predictor variables (longitude, altitude, aspect and slope).

Analysis of daily rainfall characteristics at an annual time interval as well as the wet season and dry season showed a general decrease in the total daily rainfall and total number of rain days from west to east. In terms of altitude, lower altitude raingauges received higher total daily rainfall in a higher total number of raindays compared to high altitude raingauges. On a seasonal basis, analysis of daily rainfall properties showed that for the annual and wet season, low altitude raingauges received higher total daily rainfalls in fewer raindays compared to the dry season. With respect to both altitude and aspect, raingauges positioned at similar altitudes received diverse rainfall amounts over varying number of raindays due to differing aspects.

The considered rain event properties were rain event depth, event duration and mean rain rate. On average, rain events in lower altitude raingauges have larger rainfall depths, shorter durations and higher mean event rain rates compared to higher altitude raingauges with longer event durations which are similar to the findings of Nel *et al*. (2010) in the Drakensberg. Lower altitude raingauges received higher maximum rain event depths and event rain rates, while the higher altitude raingauges showed indications of longer rain event durations. Spatial patterns of median rain event properties showed a decreasing trend from west to east of rain event depth and event durations. Characteristics of the median rain event properties across the catchment reveal that rain events within the study area have predominantly relatively short durations which is common for rain events of convective nature which contribute to approximately 80 percent of the annual rainfall for the area. These findings support the results of Nel and Sumner (2008) who found that low altitude raingauges receive higher daily rainfall and mean rainfall from individual rainfall events.

QR proved to be a useful method in providing more insightful information on the rainfall-predictor relationship in Cathedral Peak, as it analysed the complete conditional distribution of rain event depths for the area as opposed to just the mean state. QR showed that each predictor variable has a different influence in different parts of the rainfall distribution although some influences were smaller than others. In the future, a longer data record may reveal stronger statistical relationships between rain event properties and terrain for the area.

There are many peculiarities associated with the design of raingauge networks for undulating terrain for hydrological studies. The required density of a raingauge network for studying the spatial distribution of rainfall in mountains is difficult to quantify. Commonly, for accurate estimates of variability in rainfall a dense raingauge network is required which is associated with large installation and operational costs in mountains. This study shows that rainfall across the Cathedral Peak catchments is highly variable and complex where storms (frontal and convective) exist for reasons fundamentally unrelated to the terrain but are influenced to some degree when moving over the terrain. In order to capture the rapidly changing patterns of rainfall in the catchments, the raingauge networks needs to have a good representation of altitude and a number of geographical features such as aspect and slope, as well as longitude have to be considered.

Despite limitations caused missing data records in the study, within the year of rainfall data collected, a range of rain event categories were captured including at least one extreme event. Findings in this study showed large variations in rain event properties (maximum rain event depth, maximum rain event duration and maximum rain rates) across the relatively small Cathedral Peak catchment area. From this analysis, insight into areas within the catchments that receive higher rain rates, which are likely to be associated with higher runoff generation and soil erosion can be determined. An understanding of the current spatial variability of rainfall will assist in better management of the available water resources from these crucial high altitude catchments and can increase the capacity to respond to projections of change in the characteristics of events and frequency of extreme events.

7. DEVELOPMENT OF THE CATHEDRAL PEAK CATCHMENTS AS A LIVING LABORATORY: TRAINING, SKILLS TRANSFER AND KNOWLEDGE BUILDING

Besides the substantial value of the data collected in the Cathedral Peak catchments and the vast opportunities for improving hydrological understanding, the catchments have immense value as a living laboratory where training and the development of skills can take place. Over the course of the project, the catchments have been used as training ground for students, for the development and transfer of technical skills and as a common platform to stimulate integrative, interdisciplinary studies. These activities are discussed below.

7.1 Using the Cathedral Peak Research Catchments for Postgraduate and Intern Training

There is a growing need for Universities to train dynamic hydrologists who are capable of developing an understanding of the complexities of the whole hydrological system as well as the individual components and are able to work in an interdisciplinary framework when required. These training requirements are even more pressing in the southern African region where there are shortages in the number of trained hydrologists and often shortcomings in the skills level of those hydrologists. However, the training of postgraduates is often hampered by the current educational landscape which is characterized by limited facilities and resources. Added to this, is the move towards a one year Masters in Science which is a great constraint for the field based disciplines.

Given these demands and pressures on postgraduate training, opportunities provided by long term monitoring sites such as the Cathedral Peak research catchments are invaluable. The use of the catchments at the various postgraduate levels are outlined here to indicate the potential offered.

7.1.1 Honours Student Training

The Honours year is becoming an increasingly important year of skills development, training and exposure to research due to the rapidly growing undergraduate class sizes. The large undergraduate class together with the limited facilities and resources result in undergraduate students sharing equipment, having limited hands-on and practical experience. Thus, during the Honours year it is essential that students undertake hands-on practical training, have greater exposure to scientific method and rigor as well as exposure to research. The use of living laboratories such as the Cathedral Peak research catchments allows this exposure. Using living laboratories allows students to learn through experience and visualisation, allows for practical hands-on training and the inclusion of students in ongoing “umbrella” research projects. Over the course of this project, the Cathedral Peak research catchments and the data from them have been used in several aspects of the Honours program.

The Cathedral Peak catchments were selected as the catchments that were modelled in the “Advanced Hydrological Modelling” module. The long term climatic and hydrological data made the Cathedral Peak catchments an ideal example for the students to gain a greater understanding of hydrological models and process understanding on which these models are based. Field visits which included hands-on practical work further enhanced the module. The Cathedral Peak catchments were also used as the field site where the practical work related to the “Advanced Hydrological Processes” module. The combination of the baseline climatic and hydrological monitoring, together with the focused campaigns and specialised equipment in the catchments provided several field work opportunities for the module.

In addition, to the use of the Cathedral Peak catchments in the modules taken by Honours students, three Honours students have undertaken Honours research projects related to this broader project. The details of these students are provided in Table 7.1. It must be noted that all three students have continued onto Masters, two of them on this project. The long term data and ongoing monitoring at the site make it possible for Honours projects related to the catchments to be undertaken. The short time frame of the Honours research project and the misalignment of the academic and hydrological year means that Honours projects need to make use of existing data and monitoring. Going forward, it is anticipated that numerous Honours research projects will make use of the data from the catchments.

Table 7.1: Honours students trained through this project

Year	Name	Gender	Race	Involvement/Project
2015/16	Megan Taylor	F	W	The impacts of fire on the streamflow of the Cathedral Peak research catchments
2014/15	Byron Gray	M	W	Cross-calibration of raingauges
2014/15	Tiffany Aldsworth	F	W	Contribution of fog to the water budget

7.1.2 Masters and PhD level Student Training

As mentioned above, there is a push towards Masters of Science degrees being completed in one year. If this is to be adhered to, limitations are placed on the nature of the projects undertaken, with studies limited to desktop studies or those that can make use of existing data. Thus, the ongoing monitoring at the Cathedral Peak research catchments could provide scope for several Masters level research projects. In addition, for students who are willing to complete their studies in a longer time frame and wish to undertake field work, the scope offered at the Cathedral Peak research catchments with the base monitoring already in place are endless. Four students have undertaken their MSc degrees related to this project. Three have been field based projects, while one was a desk based study. The details of the students are provided in Table 7.2.

A further benefit of using living laboratories such as the Cathedral Peak catchments for postgraduate training is that they allow for the pooling of resources, expertise, capital and physical resources. This is of enormous benefit to both the students and the institutions involved. The students who have undertaken their projects to date in catchments have benefited from the expertise of scientists and technicians from both UKZN and SAEON. The pooling of capital and physical resources has allowed additional scope in the field based projects, for example, the inclusion of a high altitude fog gauge in the fog study which would not have been possible otherwise.

Table 7.2: Masters students trained through this project

Years	Name	Gender	Race	Involvement/Project
2013-2015	Feroza Morris	F	C	Improving the understanding of the spatial distribution of rainfall
2014-2016	Sibusiswe Majozi	F	A	Detection of changes
2015-2016	Byron Gray	M	W	Cross-calibration of raingauges
2015-2016	Tiffany Aldsworth	F	W	Contribution of fog to the water budget

7.1.3 Field Schools for Postgraduates

As mentioned previously, Universities are constrained by limited human, capital and physical resources. Thus, to ensure that the students trained are exiting with the necessary skills, new approaches are needed. Holding field schools for postgraduates students at various levels in living laboratory catchments such as Cathedral Peak can provide learning experiences and exposure to a greater range of specialists than what students would be normally and can relieve the pressure on the limited resources at Universities.

A winter field school for Honours students was held in the catchments from 8 to 11 July 2014. An invite for Hydrology Honours students to apply was sent to University of Venda, University of Zululand (UniZulu) and University of KwaZulu-Natal (UKZN). Seven applications were received, from the target universities. Based on the letters of motivation and available space, six students were accepted into the field school, with only five attending. Two students from UKZN attended, two from UniZul and one from University of Venda, with expertise from the Centre for Water Resources, UKZN and SAEON (Figure 7.1). The course was aimed at improving the students understanding of hydrological processes through field based measurements and practical experience. The content covered included the history of the Cathedral Peak Catchments and objectives of re-establishment, using the Cosmic Ray Probe to monitor soil moisture and calibration using gravimetric and wireless TDR sensors, introduction to energy balance techniques for actual evaporation measurements using the LAS MK II and eddy co-variance systems and designing of monitoring networks for Global Change. The feedback from the students who attended was that the field school had a positive impact on their studies and that they were exposed to new equipment, techniques and ideas. Given the success and benefit of the workshop to the students, future workshops are planned.

7.1.4 Intern training and skills development

In addition to the students who have been trained through this project, four interns have benefitted (Table 7.3). These interns have been exposed to a desk based research using the data from the catchments, field based research including the installation, collection, error checking and analysis of data. The success of the intern training could be recognized in that one of the interns completed a Honours project related to this project following her internship and has gone onto register as an MSc student in 2016. Another intern has been encourage to register in 2016 for her Hydrology Honours.

Figure 7.1: Participants in the Hydrology Honours Winter Field School held in Cathedral Peak from 8 to 11 July 2014

Table 7.3: Interns trained through this project

Year	Name	Gender	Race	Involvement
2015/16	Thivashnie Naidoo	F	I	In-service Training: Hydrological modelling and data management
2014/15	Nasiphi Ntshanta	F	A	In-service Training: Fire verification & Hydrological monitoring
2014/15	Sinthemba Ntshangase	F	A	In-service Training: Fire verification & Hydrological monitoring
2014	Megan Taylor	F	W	Fire verification

7.2 Technical Training and Skills Transfer

Technical skills transfer has been a strong component of this project. This has occurred at multiple levels. Technicians from UKZN have work alongside newly appointed technicians at SAEON, teaching them on the job, in field and in the laboratory about various approaches, deploying, calibrating and maintaining instrument networks. Academics on the program have provided advisory support to the SAEON program on a continual basis. Assistance was regularly provided to SAEON for instrument set ups in field. Table 7.4 details the individuals who have benefitted from technical training and skills transfer during the project.

Table 7.4: Technical capacity building of individuals

Name	Gender	Race	Involvement
Siphiwe Mfeka	M	A	Equipment installation, monitoring and maintenance
Matthew Becker	M	W	Equipment installation, monitoring and maintenance
Kent Lawrence	M	W	Equipment installation, monitoring and maintenance
Ofentse Mokonto	M	A	Raingauge installation
Malekeng Selala	M	A	Raingauge installation

In addition, a formal technical training workshop was hosted by SAEON for interested students and technicians from the GFW node and all other SAEON terrestrial nodes. Project team members supported this training. The purpose of the training was to capacitate SAEON technical staff and students on the SAEON equipment platform which includes sophisticated weather and flux equipment. Participants were trained on equipment logger program. SAEON Observation database orientation and meta data standards were also covered. A total of 12 people received training (Table 2.1).

Table 7.5: Trainees on the SAEON-UKZN technical training workshop 17-25 May 2015

Name	Gender	Race	Position	Department	Highest qualifications
Thami Shezi	M	A	DST-NRF Intern	SAEON GFW	Hons
Paul Gordjin	M	W	Technician	SAEON GFW	MSc
Kent Lawrence	M	W	Technician	SAEON GFW	MSc
Siphiwe Mfeka	M	A	Technical Assistant	SAEON GFW	Matric, +7yrs experience
Shaeden Gokool	M	I	PhD student	UKZN	MSc
Tercia Strydom	F	C	PhD student	SANParks/ UKZN	MSc
Margaret Koopman	F	W	Data Librarian	SAEON Fynbos	MSc
Abri de Buys	M	W	Technician	SAEON Fynbos	MSc
Rion Lerm	M	W	Technician	SAEON Ndlovu	MSc
Marco Pauw	M	W	Technician	SAEON Arid	MSc
Tshililo Ramaswiela	M	A	Technician	SAEON Arid	MSc
Susan J. van Rensburg	F	W	Node Coordinator	SAEON GFW	MSc

Skills and technical knowledge related to hydrological field instrumentation is in dire shortage currently in South Africa, with many of those considered experts nearing retirement age. Thus, this project has made an important contribution to technical training and skills transfer. Due to the relationship that has been developed between SAEON and UKZN through the course of this project, it is planned that the pooling of technical resources and continual training will continue.

7.3 Technology Transfer: Papers, Presentations and Posters

Scientific papers

The following three papers have resulted from this project and are currently under review:

Morris, F.; Toucher, M.L; Clulow, A.; Morris, C.; Kusangaya, S. and Bulcock, H. 2015. Improving the understanding of rainfall distribution and characterisation in the Cathedral Peak catchments using geo-statistical techniques. *Submitted to Water SA*.

Morris, F., Toucher, M.L., Clulow, A., Kusangaya, S. and Bulcock, H. 2015. Improving the understanding of rainfall distribution and characteristics in the Cathedral Peak catchments using quantile regression analysis. *Submitted to Water SA.*

Warburton ML. *et al*. 2015. Toward understanding the environmental change impacts on hydrological responses through long term monitoring: reestablishment of the cathedral peak research catchments, South Africa. *Submitted to WaterSA.*

Conference presentations and posters

Presentations relating to work being undertaken in this project have been given at several national conferences and one international conference, primarily by the students involved in the project. These presentations, listed by year, are:

Warburton, ML. *et al*. 2012. Hydrological modelling in the Cathedral Peak catchments. 16th SANCIAHS National Hydrology Symposium, University of Pretoria, 1-3 October 2012

Morris, F. 2013. Improving the understanding of the spatial distribution of rainfall Kirstenbosch Research centre. GSN Indibano, Cape Town 19-22 August 2013

Majozi, S. 2014. Detection of long-term climatic and hydrological trends in the Cathedral Peak Catchments. SEAON GSN Indibano. Port Elizabeth, 5-8 September 2014.

Majozi, S. 2014. Detection and attribution of long-term climatic and hydrological trends in the Cathedral Peak catchments. Global Change Conference, Port Elizabeth, 1-5 December 2014.

Majozi, S. 2014. Detection of long-tern climatic trends in the Cathedral Peak catchments. Young Water Professionals Conference. Pretoria, 16-18 November 2015.

Morris, F. 2014. Improving understanding of spatial rainfall variability in Cathedral Peak. SANCIAHS Conference. Cape Town, 1-3 September 2014.

Morris, F, Kusangaya, S, Morris, C, Warburton, M, and Clulow A. 2014. Improving the understanding of rainfall distribution and characterisation in mountainous areas using geo-statistical techniques. Global Change Conference, Port Elizabeth, 1-5 December 2014.

Janse van Rensburg, S, Everson, CS, Gordijn, PG, O'Connor, TG, Warburton, ML, Hill, T and Finch, J. 2015. Cathedral Peak global change monitoring platform – update on activities. Platform presentation, Grassland Society of Southern Africa Congress 50. Pietermaritzburg 21-23 July 2015.

Janse van Rensburg, S, Everson, CS, Gordijn, PG, O'Connor, TG, Warburton, ML, Everson, TM. 2015. The Cathedral Peak Research Catchments Long term Global Change monitoring platform: Towards understanding the future of South Africa's water tower. Perth III: Mountains of Our Future Earth. Scotland. 4-8 October 2015.

In addition to these above presentations, the research related to the project was prominent at the SAEON-GFW nodes Cathedral Peak mini symposium held in 2013 and again in 2015. Both the students and researchers involved gave presentations related to their specific aspects of the project at both symposiums.

Other presentations

In addition to the presentations made at scientific conference, annual presentations have been made on the progress on the project to EKZNW. In addition, in 2014 the work being undertaken within this project was presented in field to the National Research Foundation (NRF) Board. Policy relevance for the country was discussed in detail. This engagement provided an opportunity to profile the project at a national level. The project was very positively received by the board (http://www.saeon.ac.za/enewsletter/archives/2014/april2014/doc06). Following this visit by the NRF Board, representatives from the Department of Science and technology conducted a site visit and were briefed on the program and the associated capacity development it has enabled.

7.4 Successes, Barriers and the Way Forward

Overall, it is the opinion of the project team that this WRC proposal has been successful in terms of its objectives to advance the initiative of SAEON to reestablishment monitoring in the Cathedral Peak catchments, and to show the potential of the catchments for use as a living laboratory for training and capacity building. Through the course of the project barriers have also been identified that may hindered the further development and use of the catchments as a living laboratory, however through collective efforts and collaboration many of these can be overcome. The successes, barriers and suggestions for the way forward from lessons learnt from the SAEON initiative to re-establish the catchments and through this project are highlighted below.

Successes

The largest success related to the Cathedral Peak research catchments to date is the securing of funding for the basic and more specialised monitoring equipment. Government, through the Department of Science and Technology and NRF invested in research infrastructure that has been used to kick-start the SAEON Cathedral Peak long-term observation platform. Though funding from other sources, such as this WRC project and the PEER science grant, additions to this research infrastructure have been made. SAEON'S primary role is to provide a platform to enable global change science which they are achieving in the Cathedral Peak catchments due to the investments made in infrastructure. However, the ultimate success of this investment hinges on strong collaborations with academics and university institutions.

Through this project, there has been strong collaboration between UKZN and SAEON which has further ensured the success of the platform. The UKZN team has benefitted from the platform as well as contribute to its academic advancement. The technical skills transfer from UKZN to the SAEON technicians and the training of postgraduates through the use of the platform has been the largest success of this project. It has also provided a model for how government investment in research infrastructure, combined with academic collaboration and student support from WRC funding, can operate in unison to achieve the intended value of the platform while at the same time addressing critical knowledge and training requirements. A key success factor in moving forward will be ensuring the continuation of academic collaboration augmented with funding streams for student support.

A further success of the project has been the gathering of knowledge from scientists who worked in the catchments previously, solidifying the base of knowledge from which advancements can be made moving forward and creating an interest in the catchments with young scientists, and hopefully a new generation who will continue the research in the catchments.

Barriers

During the course of the project, four substantial barriers and concerns for the continuation of research in the Cathedral Peak catchments and the success of the platform created by SAEON were identified. Targeted strategies required to overcome these barriers have been identified where possible.

The first barrier identified is security in the research catchments. In 2015, theft and vandalism of equipment became an issue within the catchment area. This has led to compromised datasets that impacted on the long term integrity of datasets and, of more relevance in this project, impacted on student projects. Steps have already been implemented by SAEON address the situation; Meetings have been held with police and EKZNW to ensure appropriate response when incidences occur and EKZNW has undertaken to ensure planned patrols within the area. Theft proof housing for equipment has been ordered. Various alarm systems to trigger remote alerts to illegal activity in the area are being explored.

The second constraint identified was resource constraints in terms of human capital and student funding. While funding for equipment has thus far been moderately supported, human capital resource constraints hamper operations within the SAEON-GFW node, and thus the Cathedral Peak research catchments platform. The unfunded scientist and data manager posts in the SAEON node are a cause of concern. The Science post can potentially be addressed by securing an appropriate professional development grant at post-doctoral level to assist in guiding the academic program, however this would be only an interim measure. Given the importance and volume of data being generated from the platform it is highly recommended that SAEON consider funding the data manager post for the node as a critical priority. The lack of a data manager resulted in SAEON being in a compromised position to adequately engage with and deliver required data products.

The capacity building opportunities through postgraduate studies using data from or process based studies in the Cathedral Peak research catchments are enormous. However, without student funding these opportunities will not be taken up. SAEON is not a bursary funding institution, thus funding avenues and partnerships need to be explored to continue active student involvement on the platform. Given the success of the current collaboration and partnership with WRC, an opportunity exists to develop a long-term project, using a phased approach, to secure appropriate student support to augment the academic activities on the platform, while stimulating capacity development.

Linked to the human capital resource constraints, is the barrier that has been identified around data management systems. The resources to populate and improve the SAEON observation database were beyond the scope of this project. As a result these processes could not be enforced to fit the required time lines for creating an on line system to make data available for the project, leading to the data being provided on a DVD. While the data management system will be populated in the near future, it was a barrier to the project objectives. SAEON is addressing this internally and are confident that while delayed, the final product will be useful as a data archive and retrieval system.

The Way Forward

The effective management of the Cathedral Peak Research Long Term Observation Platform by SAEON is essential for realising the benefits of investments made to date. The longer the platform operates for, the more valuable it will become. This project has been critical in providing the base line from which to grow the program. The Cathedral Peak long term observation platform is focused primarily on understanding how South Africa's critical water provisioning systems may change. Moving forward, the monitoring plan recommendations from this project will be implemented, improving the reliability for the extended data record. SAEON should focus specific attention and resources on finalising an operational versions of the SAEON Observation database, while enforcing international standards of data collection, management and the documentation thereof. Continued emphasis on technical skills development and transfer should be an ongoing priority. A strong collaboration and partnership ethic has thus far been critical to the successes of the program. This should continue and mechanisms to enhance this further should be explored.

The second phase of this program should focus on further change detection as the record extends. In addition, detailed process level research, with intentional efforts to span across disciplines should be promoted. The aim would be to improve and parametrise process based models at the regional scale, integrating biodiversity, soil and earth system processes and hydrological functioning. In additional to changes in climate, predictions have being made regarding potential changes to the composition of mesic grasslands of South Africa (see Parr *et al*., 2014, Jewitt *et al*., 2015). Work focused on testing these predictions and determining change scenarios and their relative implications on water delivery are required. The inclusion of appropriate experimental manipulations should be considered.

8. GENERAL DISCUSSION AND RECOMMENDATIONS

8.1 General Discussion

During the initial stages of the project, a database of the historic data was compiled, starting from the initiation of monitoring in the catchments in the 1940s. The rainfall and streamflow data was error checked, and where possible infilled. The streamflow records were extended using hydrological modelling. The database is provided on a DVD included in the report. The database has both the original data and the infilled, extended records.

Alongside the compilation of the database, monitoring in the catchments was re-established. The automatic weather station at Mike's Pass was installed and monitoring initiated in August of 2012. The streamflow monitoring at the weirs at the outlets of Catchments IV, V, VI and VII was reinitiated in 2012. The historical array of twenty four raingauges was replicated, with Texas High intensity or Davis type tipping bucket raingauges were installed at the same sites as the historic raingauges. Later on an automatic weather station was installed at the research office at a lower altitude, and more comprehensive monitoring including soil water, fluxes and evaporation was initiated in Catchment VI. The protocols that should be adhered to were developed as a guide for SAEON moving into the future. These protocols will aid to insure that the records are consistent, processed and stored in an identical manner.

Once a detailed understanding of the historical monitoring network was achieved, a hydrological monitoring plan for the future was proposed that took into account the need to monitor for global change. Given the cost of maintaining a monitoring network, the network needed to be optimised and justified. Climatological monitoring at the two automatic weather stations should continue to ensure that a long record is available for change detection. The study on improving the spatial understanding of rainfall undertaken through this project (Chapter 6) showed the need to main the full array of raingauges due to the spatial variability of the rainfall across the catchments. Streamflow monitoring should continue in Catchments IV to VII as these can be considered control catchments. Furthermore, streamflow monitoring should be initiated in Catchments III and IX as these catchments would allow the impacts of land use changes and rehabilitation to be investigated. More in-depth monitoring covering a range of variables including soil moisture and evaporation should be undertaken in Catchment VI to allow for a focused effort that optimises the use of capital and human resources.

With the historical database established, the detection study could be undertaken. The historical temperature, rainfall and streamflow records were assessed for trends. Following which the historical records were compared to the current records to determine whether any statistically significant trends were evident between the two periods. Consistent positive trends in minimum, maximum and mean temperature across the three stations analysed indicated warming through the historic period. Due to temperature records for only Mike's Pass meteorological station being available for the current period, it was not possible to conclusively determine if changes were evident between the historical and current periods.

Trends in the historical rainfall records at a daily and monthly level indicated a drying through the historical record, particularly in autumn. A comparison of the historical rainfall period to the rainfall available for the current period showed an increase in the number of raindays in summer and winter, an increase in the number of events greater than 20 mm in summer and autumn and an increase in the 2-day maximum rainfall. These results begin to indicate changes in the rainfall patterns and extremes, however, they do not give an indication of whether there is a general wetting or drying trend between the historical and current period.

Decreasing trends are evident in the historical streamflow which correspond to the drying trends shown in the historical rainfall. During the historical period analysed the land use in the catchments assessed remained constant, thus it is reasoned that the intensification of the trends in rainfall through the hydrological cycle are the cause behind the negative trends being evident in streamflow across all time steps and seasons while a few statistically significant negative trends are evident in rainfall. Catchments IV, V and VI where monitoring has resumed have remained as grassland, Catchment VII was planted to commercial forestry for a short period but has been rehabilitated to grassland. Monitoring in Catchments III and IX, where it would be possible to determine the influence of land use change in comparison to climate change, has not yet resumed. Given this, and the short records for the current period it was not possible to undertake an attribution study at this stage.

The second study within the project that made use of the database was an investigation to improve the spatial understanding of the rainfall distribution across the research area. The first component of the study used the historical monthly rainfall records and geostatistics to improve the understanding of the spatial distribution of rainfall. Results indicated that the rainfall across the catchments is lower than that estimated by Schulze (1976). These results corresponded to the results from the detection study which showed a decreasing trend in rainfall across the catchments. A relationship between rainfall, longitude and altitude was shown, with an east to west spatial gradient in annual and wet season rainfall, with higher rainfalls in the west. For the dry season, the relationship between rainfall and altitude was stronger than between rainfall, longitude and altitude. During the dry season a rainfall pattern of higher rainfalls on the ridges and lower rainfall in the valleys was evident. The study recognised the limitations of using monthly time step data, thus a further study used the current rainfall record to use rain event properties to improve the understanding of the spatial distribution of rainfall. From west to east, a pattern of a decrease in the daily total rainfall, number of raindays, rain event depth and rain event duration was observed. It was further shown that lower altitudes receive higher total rainfalls, greater number of raindays, higher maximum rain event depths and event rain rates. While higher altitudes have longer rain event durations. The rainfall record available for the current period was short, thus these results need further investigation and confirmation once a longer record is available.

Throughout the project, capacity building and technical skills transfer has been a focus. The team from UKZN and SAEON have worked closely alongside each other with the SAEON technicians gaining knowledge and experience from the more experienced UKZN. The linking of an academic research team with a team focused on the monitoring and collection of data has resulted in an efficient use of both human and capital resources. The successful collaboration provides an example of the potential provided by the SAEON long term monitoring platform.

8.2 Achievement of Objectives

The project objectives have been fully achieved with the exception of Aim 4. The relevant chapters that address each of the aims are given in Table 8.1. Aim 4 was not fully addressed in that the results of the detection study were inconclusive due to the short length of the current records, thus the attribution study alluded to in the aim could not be undertaken.

Table 8.1: Relevant chapters from the report that address each of the project aims

AIM	Chapter
7. To compile a database of relevant historic data collected over the past 50 years from the Cathedral Peak research catchments.	Chapter 2 and 3, attached DVD
8. To infill and extend the historical rainfall and streamflow record of the Cathedral Peak research catchments to the present.	Chapter 3; attached DVD
9. 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.	Chapter 4
10. To determine whether any changes in hydrological response are already evident, and to understand the underlying causes.	Chapter 5
11. To improve the understanding of rainfall distribution across the escarpment.	Chapter 6
12. To develop the Cathedral Peak research catchments into a living laboratory for undergraduate and postgraduate student training as well as for technical skills transfer and knowledge building.	Chapter 7

8.3 Recommendations

The key recommendation from this project is that the SAEON initiative to further the development of the Cathedral Peak long term observation platform should be supported and encouraged, and through collaborative projects the full potential of the platform to further hydrological understanding should be explored. It needs to recognised that the longer the platform operates for, the more valuable it will become. However, it is only through strong collaboration and partnerships that the full potential of the platform will be achieved. Mechanisms to enhance the development of the platform and collaborations should be further explored.

Linked to this, a recommendation from the project is that mechanisms to secure postgraduate student funding to support student activities on the platform need to be investigated. Beyond this, funding to secure a scientist post and a data managers post at the GFW-node of SAEON need to be explored as these are crucial to supporting the student activities on the platform. Use of the Cathedral Peak catchments as a living laboratory for postgraduate field schools should continue, with the development of inter-disciplinary global change field schools being pursued.

Given the technical skills shortage currently facing South Africa, the continued emphasis on technical skills development and transfer using the catchments to gain hands-on experience and learning opportunities should be an ongoing priority.

With this project gathering the historical data and knowledge, a base has been provided for future studies which should focus on:

- Further change detection as the record extends, and attribution studies to determine the cause of the change.
- Whether changes in the rainfall : runoff response ratios are evident given the changes in the rainfall patterns as well as the influence of degradation and restoration on the rainfall : runoff response ratios.
- Detailed process level research, with intentional efforts to span across disciplines.
- With these leading to the improvement of existing and new models both in the description of processes and parametrisation of the models.
- The consequences of changes in rainfall and streamflow for downstream water delivery, particularly in the drier months.

With the advance of process based models, the impacts of change can be further explored thereby providing improved information and understanding to ensure resilient and adaptive management of water resources.

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APPENDIX A

Timeline of activities in the Cathedral Peak Catchments I-X

Year	Month	I	II	III	IV	V	VI	VII	VIII	IX	X
1938	Aug	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt
1947	Sept		Burnt								
1948	Aug				Burnt						
1948	Oct		Streamflow recording started								
1949	Aug	Burnt	Burnt								
1949	Sept			Burnt	Burnt & IV BR started recording	Burnt	Burnt	Burnt	Burnt		Burnt
1949	Oct				IV AW started recording						
1950	Jul	I CR started recording									
1950	Aug	I AW started recording		III AW & III BR started recording		V-VI AW started recording	V-VI AW & VI-VIIAW started recording	VI-VII AW started recording			
1950	Oct		II CW started recording		IV-V CW started recording	IV-V CW started recording					
1951	Jan	Streamflow recording started									
1951	Mar		Planting started								
1951	Aug	Burnt		Burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt
1952	Apr		Weir cleaned								
1952	May			Streamflow recording started							
1952	Jul									Burnt	
1952	Aug					Streamflow recording started					
1953	Feb						VI-VII CR started recording	VI-VII CR & streamflow started recording			
1953	Mar		Weir cleaned	Weir cleaned			VI BR started recording	VII BR started recording			
1953	Apr		Weir cleaned								

1953	May			Burnt							
1953	Aug				Part burnt	Part burnt					
1953	Sept				Part burnt	Burnt		Burnt			
1953	Oct	Burnt					Burnt				
1953	Nov				Burnt						Burnt
1954	Mar									IX AW recording started	
1954	Jun									IX BR & IX CR recording started	
1954	Jul								Burnt	Part burnt	
1954	Aug	Part burnt					Streamflow recording started				
1954	Oct	Part burnt								Streamflow recording started	
1954	Nov	Cattle in									
1955	Apr	Cattle out									
1955	Jul						Burnt				X AW & X CW recording started
1955	Aug				Burnt						
1955	Sept	Weir cleaned		Weir cleaned	Weir cleaned	Weir cleaned					
1955	Oct	Part burnt & Cattle in				Burnt					
1955	Nov							Burnt	Burnt		Burnt
1956	May	Cattle out									
1956	Jul		Weir cleaned		Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned		Weir cleaned	
1956	Aug	Burnt		Burnt	Burnt	Burnt	Burnt	Burnt	Burnt		Burnt
1956	Sept									Burnt	Streamflow recording started
1956	Oct	Cattle in									
1956	Dec									Weir cleaned	
1957	Mar					Weir cleaned					
1957	Apr	Weir cleaned		Weir cleaned	Weir cleaned		Weir cleaned	Weir cleaned		Weir cleaned	Weir cleaned
1957	May		Weir cleaned								
1957	Jun			Burnt	Burnt			Burnt			Burnt
1957	Jul						Burnt				
1957	Aug					Burnt					
1957	Sept	Part burnt & Cattle in									

1958	May	Cattle out									
1958	Sept	Part burnt & weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Burnt & weir cleaned	Weir cleaned		Weir cleaned	Weir cleaned
1958	Oct	Cattle in									
1959	Jan			Planting started							
1959	May	Cattle out									
1959	Jul				Burnt	Burnt					
1959	Sept							Burnt			Burnt
1959	Oct	Part burnt & Cattle in									
1960	Sept	Part burnt									
1960	Oct	Cattle in									
1961	Jul				Burnt						
1961	Aug					Burnt					Burnt
1961	Sept	Part burnt					Burnt	Burnt			
1961	Oct	Cattle in									
1962	Feb	Weir cleaned									
1962	May		Weir cleaned			Weir cleaned					
1962	Sept	Part burnt									
1962	Nov	Cattle in									
1963	May				Part burnt	Part burnt	Part burnt		Part burnt		
1963	Jun	Part burnt & Cattle out	Part burnt								
1963	Sept	Part burnt & weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned		Weir cleaned	Weir cleaned
1963	Oct				Burnt	Burnt	Burnt	Burnt	Burnt & streamflow recording started		Burnt
1963	Nov	Cattle in									
1964	May	Cattle out									
1964	Aug			Part burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt
1964	Sept	Part burnt							VIIIAW, VIIIBR & VIIICW recording started		
1964	Oct	Cattle in		Pruning started							
1965	Apr	Cattle out									
1965	Jun						Part burnt			Part burnt	Burnt
1965	Sept	Part burnt & weir cleaned			Burnt	Burnt	Part burnt	Burnt	Burnt		
1965	Oct	Cattle in	Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned		

1965	Nov									Weir cleaned	Weir cleaned
1965	Dec		Thinning								
1966	Mar	Cattle out									
1966	Jul		Thinning								
1966	Sept	Part burnt & weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Burnt & weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned
1966	Dec							Planted catchment			
1967	May	Cattle out									
1967	Jul										
1967	Sept		Pruning			Burnt					
1967	Oct	Part burnt							Burnt		Burnt
1967	Nov				Burnt		Burnt				
1967	Dec	Cattle in									
1968	Mar	Cattle out									
1968	May			Pruning							
1968	Aug	Part burnt									
1968	Oct	Cattle in									
1969	Jan			Thinning							
1969	Mar		Pruning	Pruning							
1969	Apr	Cattle out									
1969	Sept		Pruning		Burnt	Burnt	Burnt				
1969	Oct	Part burnt & Cattle in	Thinning						Burnt		Burnt
1970	Feb	Cattle out									
1970	Apr	Weir cleaned	Pruning & thinning, & weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned
1970	Oct	Part burnt									
1971	Feb	Cattle out									
1971	Aug	Weir cleaned			Weir cleaned				Weir cleaned	Weir cleaned	
1971	Sept	Part burnt			Burnt	Burnt					
1971	Oct	Cattle in									Burnt
1972	Jan			Thinning started							
1972	Apr	Cattle out									
1972	Aug	Weir cleaned		Weir cleaned				Weir cleaned	Weir cleaned	Weir cleaned	Weir cleaned
1972	Sept			Part burnt			Burnt	Burnt			
1972	Oct	Part burnt & cattle in							Burnt		
1973	Feb										XBW started recording
1973	Mar	Cattle out									
1973	Aug	I BR started									XCR started

		recording									recording
1973	Sept	Weir cleaned, part burnt & cattle in	Weir cleaned		Weir cleaned	Weir cleaned	Weir cleaned				
1973	Oct				Burnt	Burnt					Burnt
1974	Feb	Cattle out									
1974	Aug			Thinning started							
1974	Nov	Part burnt & cattle in	Weir cleaned				Burnt		Burnt	Weir cleaned	Weir cleaned
1975	Jan		Thinning started								
1975	Mar			Pruning started							
1975	May										
1975	Aug							Felling started			
1975	Sept	Part burnt		Weir cleaned	Weir cleaned & Burnt	Burnt		Felling completed			Burnt
1975	Oct								Burnt		
1976	Feb										
1976	Sept	Part burnt	Weir cleaned								
1976	Oct								Burnt		
1976	Nov						Burnt				
1977	Mar			Thinning started							
1977	Jun			Part burnt							
1977	Sept	Part burnt		Weir cleaned	Burnt	Burnt					Burnt
1978	Feb										
1978	Sept		Weir cleaned	Weir cleaned							
1978	Oct	Part burnt					Burnt		Burnt		
1979	May										
1979	Jul		Water quality sampling started	Water quality sampling started							
1979	Sept	Part burnt		Weir cleaned							
1979	Oct		Weir cleaned	Thinning started	Burnt	Burnt					Burnt
1980	Mar			Weir cleaned & thinning							
1980	Sept				Water quality sampling		Water quality sampling	Burnt & Water quality		Water quality sampling	

					started		started	sampling started		started	
1980	Oct						VIB & VIC start recording	VIIB start recording		IXC s start recording	
1981	Feb								Burnt		
1981	May					Burnt					
1981	Jul		Felling started								
1981	Aug				Burnt						Burnt
1981	Sept	Burnt	Part burnt	Burnt			Burnt	Burnt			
1982	Aug				Burnt						
1982	Sept			Weir cleaned & planting Erogrostis curvula starts							
1983	Feb								Burnt		
1983	May					Burnt					
1983	Aug							Burnt			Burnt
1983	Dec		Planting Erogrostis curvula starts								
1984	Jun	Burnt					Burnt				
1984	Aug				Burnt						
1984	Oct										
1985	Mar								Burnt		
1985	Jun					Burnt	Burnt				
1985	Sept							Burnt			Burnt
1985	Oct	I AW, I BR & I CR & streamflow ceased recording		III BR ceased recording			VIB & VIBR ceased recording	VIIB & VIIBR ceased recording	VIIICW & VIIIBR ceased recording	IXBR ceased recording	XB, XC & XCR & streamflow ceased recording
1986	Feb		Weir cleaned		Weir cleaned	Weir cleaned	Weir cleaned		Weir cleaned	Weir cleaned	
1986	May			Burnt			Burnt				
1986	Aug										
1986	Sept	Burnt			Burnt						
1987	Mar								Burnt		
1987	Jun	Burnt				Burnt	Burnt				
1987	Aug			Burnt							
1987	Sept							Burnt			Burnt
1988	May	Burnt	Burnt				Burnt				
1988	Jun		Part burnt								
1988	Aug				Burnt						
1989	Mar								Burnt		
1989	May					Burnt	Burnt				

1989	Jun										
1989	Aug							Burnt			Burnt
1990	Apr		Weir cleaned								
1990	Jul			Weir cleaned							
1990	Aug						Burnt				
1990	Sept	Burnt	Burnt	Burnt	Burnt	Burnt					
1990	Nov			Weir cleaned		Weir cleaned			Weir cleaned		
1990	Dec		Weir cleaned								
1991	May	Burnt	Burnt			Burnt	Burnt		Burnt	Burnt	
1991	Aug			Burnt				Burnt			Burnt
1992	Jun						Burnt				
1992	Aug	Burnt	Burnt								
1993	Feb								Burnt		
1993	Apr										Burnt
1993	May					Burnt					
1993	Aug			Burnt	Burnt						
1993	Oct						Burnt	Burnt			
1994	May	Burnt	Burnt								
1994	Jun						Burnt				
1994	Aug		Burnt								
1994	Oct				Burnt	Burnt					
1995	Jan		Burnt				Burnt	Burnt			
1995	Feb								Burnt		
1995	Apr										Burnt
1995	May									Burnt	
1995	Jul	Burnt		Burnt	Burnt	Burnt					
1996	Jun	Burnt					Burnt				
1997	Jun			Burnt	Burnt			Burnt		Burnt	
1997	Jul						Burnt		Burnt		
1998	Jun		Burnt				Burnt				
1998	Aug	Burnt									
1998	Sept										Burnt
1998	Oct					Burnt					
1999	Mar								Burnt		
1999	Jun						Burnt				
1999	Sept				Burnt						

1999	Oct							Burnt			
2000	Jan	Burning programme revised.	Burning programme revised	Burning programme revised	Burning programme revised	Burning programme revised	Burning programme revised	Burning programme revised	Burning programme revised	Burning programme revised	Burning programme revised
2000	May	Burnt				Burnt					
2000	Jun						Burnt				
2000	Sept										Burnt
2001	Sept								Burnt		
2002	May			Burnt							
2002	Jul					Burnt	Burnt				
2002	Aug							Burnt	Burnt		
2002	Sept									Burnt	Burnt
2004	Jun		Burnt	Burnt							
2004	Aug	Burnt	Burnt		Burnt	Burnt			Burnt		
2005	Jul									Burnt	Burnt
2006	Jul	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt	Burnt		Burnt

APPENDIX B Timeline of activities in the Cathedral Peak Catchments XI-XV

Year	Month	XI	XII	XIII	XIV	XV
1972	Nov				XIVG start recording	XVE starts recording
1973	Jan	XIB, XIC & XIE start recording	XIIA & XIIB start recording	XIIIA, XIIIB, XIIIC & XIIID start recording	XIVC, XIVE & XIVF start recording	
1975	May					XVB, XVC, XVD, XVF & XVG start recording
1975	Sept	Streamflow recording commenced & burnt	Start Streamflow recording		Start Streamflow recording	Start Streamflow recording
1975	Dec				XIVGR start recording	
1976	Mar			Start Streamflow recording		
1976	Dec					XVER starts recording
1977	Sept	Burnt				
1979	Sept	Burnt				
1981	May	Burnt				
1981	Aug		Burnt			
1982	Jun	Burnt	Burnt			
1983	Jun	Burnt				
1983	Aug				Burnt	
1984	Jun	Burnt				
1985	May	Burnt		Burnt		
1985	Aug				Burnt	
1985	Oct	XIB & ceased streamflow recording	XIIA, XIIB & ceased streamflow recording	XIIIA, XIIIB & XIIIC ceased recording	XIVC, XIVE, XIVF & XIVG ceased recording	XVB, XVC, XVD, XVE, XVER, XVF & XVG ceased recording
1986	May			Streamflow recording automated	Streamflow recording automated	Streamflow recording automated
1986	Jun	Burnt	Part burnt			
1987	Mar	Burnt				
1987	Sept				Burnt	
1988	Jun	Burnt				
1989	Jun	Burnt				
1989	Aug		Burnt			
1990	Jun	Burnt				
2000	Jan	Burning programme revised to focus on biodiversity conservation.	Burning programme revised to focus on biodiversity conservation.	Burning programme revised to focus on biodiversity conservation.	Burning programme revised to focus on biodiversity conservation.	Burning programme revised to focus on biodiversity conservation.
2000	Jun	Burnt				
2000	Sept				Burnt	
2001	Aug					Burnt
2001	Sept	Burnt	Burnt			
2004	Aug	Burnt	Burnt	Burnt	Burnt	
2005	Jun	Burnt	Burnt			
2006	Jul	Burnt				

APPENDIX C: ACRU Model Input Parameters

Catchment	Mean Monthly Maximum Temperature (°C)											
	Jan	Feb	Mar	May	Apr	Jun	Jul	Aug	Sep	Oct	Nov	Dec
III	22.0	21.0	20.0	18.5	16	13.5	13.5	16	18.5	19.5	20.5	22
IV	21.6	21.1	20.1	17.64	15.14	12.64	13.09	15.14	18.09	19.09	19.64	21.14
VI	22.0	22.0	20.7	18.00	16.00	13.00	13.67	16.00	18.67	19.67	20.00	22.00
VII	23.4	23.0	21.5	19.36	17.00	14.36	14.45	17.00	19.45	20.45	21.00	23.00
XI	23.0	21.5	21.0	18	15.5	13.5	13.5	15.5	18	19	20	20
Catchment	Mean Monthly Minimum Temperature (°C)											
	Jan	Feb	Mar	May	Apr	Jun	Jul	Aug	Sep	Oct	Nov	Dec
III	10.5	10.5	9.5	6.5	3.5	0.5	0.5	2.5	5.00	7	8.5	10
IV	10.09	10.05	9.05	6.50	4.41	1.41	1.41	2.95	5.00	7.05	8.05	9.59
VI	10.67	10.33	9.33	7.00	4.33	1.33	1.33	2.67	5.00	7.33	8.33	9.67
VII	11.45	10.91	9.91	7.00	3.55	0.55	0.55	2.45	5.00	7.55	8.91	10.45
XI	10.5	10.5	9.5	7	4.5	1.5	2.0	3.5	5.00	7	8.5	
Catchment	Monthly Apan Evaporation (mm)											
	Jan	Feb	Mar	May	Apr	Jun	Jul	Aug	Sep	Oct	Nov	Dec
III	162.5	278	252	112	97	84.5	97.5	131	147	152.5	151	175
IV	156	141.5	122	111.23	96.14	83.18	96.64	130.09	144.00	147.77	145.00	169.46
VI	168.5	141.5	130.5	112.67	97.00	84.33	97.00	130.67	146.67	150.67	151.33	175.00
VII	168.5	141	130.67	114.82	98.36	85.91	98.36	131.46	150.82	157.18	160.00	182.73
XI	162.5	135	127.5	112.5	98	85	97.5	131	146	147.5	150	177
Catchment	Mean Monthly Rainfall (mm)											
	Jan	Feb	Mar	May	Apr	Jun	Jul	Aug	Sep	Oct	Nov	Dec
III	229	220	194	75	27	14.5	11.5	26.5	53	113	163	193
IV	227	181	157	75	26.5	14.5	12	27	52	113	147.5	160
VI	186	181	156	62	23.5	13	10.5	24	44	90	130.5	155.5
VII	186	174	148.5	61	23.5	13	10.5	23	40.5	87	127	156
XI	164.5	174	141	62	22	12.5	10.5	23	40	85	119.5	149

APPENDIX D : Specifications of the CR1000 datalogger

CR1000 Specifications

Electrical specifications are valid over a -25° to +50°C, non-condensing environment, unless otherwise specified. Recalibration recommended every three years. Critical specifications and system configuration should be confirmed with Campbell Scientific before purchase.

PROGRAM EXECUTION RATE
10 ms to one day @ 10 ms increments

ANALOG INPUTS (SE1-SE16 or DIFF1-DIFF8)
8 differential (DF) or 16 single-ended (SE) individually configuredinput channels. Channel expansion provided by optional analog multiplexers.

RANGES and RESOLUTION: Basic resolution (Basic Res) is the A/D resolution of a single A/D conversion. A DIFF measurement with input reversal has better (finer) resolution by twice than Basic Res.

Range (mV)[1]	*DF Res (μV)*[2]	*Basic Res (μV)*
±5000	667	1333
±2500	333	667
±250	33.3	66.7
±25	3.33	6.7
±7.5	1.0	2.0
±2.5	0.33	0.67

[1]Range overhead of ~9% on all ranges guarantees that full-scale values will not cause over range.
[2]Resolution of DF measurements with input reversal.

ACCURACY[3]:
±(0.06% of reading + offset), 0° to 40°C
±(0.12% of reading + offset), -25° to 50°C
±(0.18% of reading + offset), -55° to 85°C (-XT only)

[3]Accuracy does not include the sensor and measurement noise. Offsets are defined as:
Offset for DF w/input reversal = 1.5•Basic Res + 1.0 μV
Offset for DF w/o input reversal = 3•Basic Res + 2.0 μV
Offset for SE = 3·Basic Res + 3.0 μV

ANALOG MEASUREMENT SPEED:

Integration Type/Code	*Integration Time*	*Settling Time*	*Total Time*[4] *SE w/ No Rev*	*Total Time*[4] *DF w/ Input Rev*
250	250 μs	450 μs	~1 ms	~12 ms
60 Hz[5]	16.67 ms	3 ms	~20 ms	~40 ms
50 Hz[5]	20.00 ms	3 ms	~25 ms	~50 ms

[4]Includes 250 μs for conversion to engineering units.
[5]AC line noise filter.

INPUT NOISE VOLTAGE: For DF measurements with input reversal on ±2.5 mV input range (digital resolution dominates for higher ranges).
250 μs Integration: 0.34 μV RMS
50/60 Hz Integration: 0.19 μV RMS

INPUT LIMITS: ±5 Vdc

DC COMMON MODE REJECTION: >100 dB

NORMAL MODE REJECTION: 70 dB @ 60 Hz when using 60 Hz rejection

INPUT VOLTAGE RANGE W/O MEASUREMENT CORRUPTION: ±8.6 Vdc max.

SUSTAINED INPUT VOLTAGE W/O DAMAGE: ±16 Vdc max.

INPUT CURRENT: ±1 nA typical, ±6 nA max. @ 50°C; ±90 nA @ 85°C

INPUT RESISTANCE: 20 GΩ typical

ACCURACY OF BUILT-IN REFERENCE JUNCTION THERMISTOR (for thermocouple measurements):
±0.3°C, -25° to 50°C
±0.8°C, -55° to 85°C (-XT only)

ANALOG OUTPUTS (VX1-VX3)
3 switched voltage, sequentially active only during measurement.

RANGE AND RESOLUTION:

Channel	*Range*	*Resolution*	*Current Source/Sink*
(VX 1–3)	±2.5 Vdc	0.67 mV	±25 mA

ANALOG OUTPUT ACCURACY (VX):
±(0.06% of setting + 0.8 mV), 0° to 40°C
±(0.12% of setting + 0.8 mV), -25° to 50°C
±(0.18% of setting + 0.8 mV), -55° to 85°C (-XT only)

VX FREQUENCY SWEEP FUNCTION: Switched outputs provide a programmable swept frequency, 0 to 2500 mv square waves for exciting vibrating wire transducers.

PERIOD AVERAGE
Any of the 16 SE analog inputs can be used for period averaging. Accuracy is ±(0.01% of reading + resolution), where resolution is 136 ns divided by the specified number of cycles to be measured.

INPUT AMPLITUDE AND FREQUENCY:

Voltage Gain	*Input Range (±mV)*	*Signal (peak to peak) Min. (mV)*[6]	*Signal (peak to peak) Max (V)*[7]	*Min Pulse Width (μV)*	*Max*[8] *Freq (kHz)*
1	250	500	10	2.5	200
10	25	10	2	10	50
33	7.5	5	2	62	8
100	2.5	2	2	100	5

[6]Signal centered around Threshold (see PeriodAvg() instruction).
[7]With signal centered at the datalogger ground.
[8]The maximum frequency = 1/(twice minimum pulse width) for 50% of duty cycle signals.

RATIOMETRIC MEASUREMENTS
MEASUREMENT TYPES: Provides ratiometric resistance measurements using voltage excitation. 3 switched voltage excitation outputs are available for measurement of 4- and 6-wire full bridges, and 2-, 3-, and 4-wire half bridges. Optional excitation polarity reversal minimizes dc errors.

RATIOMETRIC MEASUREMENT ACCURACY:[9,10,11]
±(0.04% of Voltage Measurement + Offset)

[9]Accuracy specification assumes excitation reversal for excitation voltages < 1000 mV. Assumption does not include bridge resistor errors and sensor and measurement noise.

[10]Estimated accuracy, ΔX (where X is value returned from the measurement with Multiplier = 1, Offset = 0):
BrHalf() instruction: $\Delta X = \Delta V_1/V_X$
BrFull() instruction $\Delta X = 1000 \cdot \Delta V_1/V_X$, expressed as $mV \cdot V^{-1}$.
ΔV^{-1} is calculated from the ratiometric measurement accuracy. See Resistance Measurements Section in the manual for more information.

[11]Offsets are defined as:
Offset for DIFF w/input reversal = 1.5•Basic Res + 1.0 μV
Offset for DIFF w/o input reversal = 3•Basic Res + 2.0 μV
Offset for SE = 3•Basic Res + 3.0 μV
Excitation reversal reduces offsets by a factor of two.

PULSE COUNTERS (P1-P2)
2 inputs individually selectable for switch closure, high frequency pulse, or low-level ac. Independent 24-bit counters for each input.

MAXIMUM COUNTS PER SCAN: 16.7×10^6

SWITCH CLOSURE MODE:
Minimum Switch Closed Time: 5 ms
Minimum Switch Open Time: 6 ms
Max. Bounce Time: 1 ms open w/o being counted

HIGH-FREQUENCY PULSE MODE:
Maximum Input Frequency: 250 kHz
Maximum Input Voltage: ±20 V
Voltage Thresholds: Count upon transition from below 0.9 V to above 2.2 V after input filter with 1.2 μs time constant.

LOW-LEVEL AC MODE: Internal ac coupling removes ac offsets up to ±0.5 Vdc.
Input Hysteresis: 12 mV RMS @ 1 Hz
Maximum ac Input Voltage: ±20 V
Minimum ac Input Voltage:

Sine Wave (mV RMS)	*Range(Hz)*
20	1.0 to 20
200	0.5 to 200
2000	0.3 to 10,000
5000	0.3 to 20,000

DIGITAL I/O PORTS (C1-C8)
8 ports software selectable, as binary inputs or control outputs. Provide on/off, pulse width modulation, edge timing, subroutine interrupts / wake up, switch closure pulse counting, high frequency pulse counting, asynchronous communications (UARTs), and SDI-12 communications. SDM communications are also supported.

LOW FREQUENCY MODE MAX: <1 kHz

HIGH-FREQUENCY MODE MAX: 400 kHz

SWITCH-CLOSURE FREQUENCY MAX: 150 Hz

EDGE TIMING RESOLUTION: 540 ns

OUTPUT VOLTAGES (no load): high 5.0 V ±0.1 V; low <0.1

OUTPUT RESISTANCE: 330 Ω

INPUT STATE: high 3.8 to 16 V; low -8.0 to 1.2 V

INPUT HYSTERESIS: 1.4 V

INPUT RESISTANCE: 100 kΩ with inputs <6.2 Vdc
220 Ω with inputs ≥6.2 Vdc

SERIAL DEVICE/RS-232 SUPPORT: 0 TO 5 Vdc UART

SWITCHED 12 VDC (SW-12)
1 independent 12 Vdc unregulated source is switched on and off under program control. Thermal fuse hold current = 900 mA at 20°C, 650 mA at 50°C, 360 mA at 85°C.

CE COMPLIANCE
STANDARD(S) TO WHICH CONFORMITY IS DECLARED:
IEC61326:2002

COMMUNICATIONS
RS-232 PORTS:
DCE 9-pin: (not electrically isolated) for computer connection or connection of modems not manufactured by Campbell Scientific.
COM1 to COM4: 4 independent Tx/Rx pairs on control ports (non-isolated); 0 to 5 Vdc UART
Baud Rates: selectable from 300 bps to 115.2 kbps.
Default Format: 8 data bits; 1 stop bits; no parity
Optional Formats: 7 data bits; 2 stop bits; odd, even parity

CS I/O PORT: Interface with telecommunications peripherals manufactured by Campbell Scientific.

SDI-12: Digital control ports C1, C3, C5, and C7 are individually configured and meet SDI-12 Standard v 1.3 for datalogger mode. Up to 10 SDI-12 sensors are supported per port.

PERIPHERAL PORT: 40-pin interface for attaching CompactFlash or Ethernet peripherals

PROTOCOLS SUPPORTED: PakBus, AES-128 Encrypted PakBus, Modbus, DNP3, FTP, HTTP, XML, HTML, POP3, SMTP, Telnet, NTCIP, NTP, Web API, SDI-12, SDM.

SYSTEM
PROCESSOR: Renesas H8S 2322 (16-bit CPU with 32-bit internal core running at 7.3 MHz)

MEMORY: 2 MB of flash for operating system; 4 MB of battery-backed SRAM for CPU usage and final data storage; 512 kB flash disk (CPU) for program files.

REAL-TIME CLOCK ACCURACY: ±3 min. per year. Correction via GPS optional.

REAL-TIME CLOCK RESOLUTION: 10 ms

SYSTEM POWER REQUIREMENTS
VOLTAGE: 9.6 to 16 Vdc

INTERNAL BATTERIES: 1200 mAh lithium battery for clock and SRAM backup that typically provides three years of backup

EXTERNAL BATTERIES: Optional 12 Vdc nominal alkaline and rechargeable available. Power connection is reverse polarity protected.

TYPICAL CURRENT DRAIN at 12 Vdc:
Sleep Mode: < 1 mA
1 Hz Sample Rate (1 fast SE meas.): 1 mA
100 Hz Sample Rate (1 fast SE meas.): 6 mA
100 Hz Sample Rate (1 fast SE meas. w/RS-232 communication): 20 mA
Active external keyboard display adds 7 mA (100 mA with backlight on).

PHYSICAL
DIMENSIONS: 23.9 x 10.2 x 6.1 cm (9.4 x 4 x 2.4 in); additional clearance required for cables and leads.

MASS/WEIGHT: 1 kg / 2.1 lb

WARRANTY
3 years against defects in materials and workmanship.

APPENDIX E: Automatic weather station program running on the CR1000 datalogger

```
'CR1000
'Cathedral Peak SAEON weather station
'Output Tables 5 min, hourly, daily
'Scan interval 10 sec
'Declare Variables and Units
Dim WindCorr
Dim NowMin
Dim Modem
Public RTime(9)
Public BattV
Public PTemp_C
Public WS_ms
Public WindDir
Public TRHData(2)
Public NR_Wm2
Public CNR_Wm2
Public SlrUV
Public Rain_mm
Public VW
Public PA_uS
Public VW_2
Public PA_uS_2
Public VW_3
Public PA_uS_3
Public VW_4
Public PA_uS_4
Public VW_5
Public PA_uS_5
Public VW_6
Public PA_uS_6
Public T107_C
Public Rain_mm_2

Alias TRHData(1)=AirTC
Alias TRHData(2)=RH

Units BattV=Volts
Units PTemp_C=Deg C
Units WS_ms=meters/second
Units WindDir=degrees
Units NR_Wm2=W/m^2
```

```
Units CNR_Wm2=Watts/meter^2
Units SlrUV=umol
Units Rain_mm=mm
Units PA_uS=uSec
Units PA_uS_2=uSec
Units PA_uS_3=uSec
Units PA_uS_4=uSec
Units PA_uS_5=uSec
Units PA_uS_6=uSec
Units T107_C=Deg C
Units Rain_mm_2=mm
Units AirTC=Deg C
Units RH=%

'Define Data Tables
DataTable(Five_min,True,-1)
  DataInterval(0,5,Min,10)
  WindVector (1,WS_ms,WindDir,FP2,False,0,0,0)
  FieldNames("WS_ms_S_WVT,WindDir_D1_WVT,WindDir_SD1_WVT")
  Average(1,AirTC,FP2,False)
  Sample(1,RH,FP2)
  Average(1,NR_Wm2,FP2,False)
  Average(1,SlrUV,FP2,False)
  Totalize(1,Rain_mm,FP2,False)
EndTable

DataTable(Hourly,True,-1)
  DataInterval(0,60,Min,10)
  WindVector (1,WS_ms,WindDir,FP2,False,0,0,0)
  FieldNames("WS_ms_S_WVT,WindDir_D1_WVT,WindDir_SD1_WVT")
  Average(1,AirTC,FP2,False)
  Sample(1,RH,FP2)
  Average(1,NR_Wm2,FP2,False)
  Average(1,SlrUV,FP2,False)
  Totalize(1,Rain_mm,FP2,False)
EndTable

DataTable(Daily,True,-1)
  DataInterval(0,1440,Min,10)
  Minimum(1,BattV,FP2,False,False)
  WindVector (1,WS_ms,WindDir,FP2,False,0,0,0)
  FieldNames("WS_ms_S_WVT,WindDir_D1_WVT,WindDir_SD1_WVT")
  Maximum(1,WS_ms,FP2,False,False)
  Maximum(1,AirTC,FP2,False,False)
  Minimum(1,AirTC,FP2,False,False)
```

```
  Maximum(1,RH,FP2,False,False)
  Minimum(1,RH,FP2,False,False)
  Maximum(1,NR_Wm2,FP2,False,False)
  StdDev(1,CNR_Wm2,FP2,False)
  Maximum(1,SlrUV,FP2,False,False)
  Totalize(1,Rain_mm,FP2,False)
EndTable

'Main Program
BeginProg
  'Main Scan
  SW12 (1)
  Scan(10,Sec,1,0)
    'Modem on between 11h00 and 13h00
    RealTime(RTime(1))
    '1=year, 2=month, 3=day of month, 4=hour of day, 5=minutes,
    '6=seconds, 7=microseconds, 8=day of week, 9=day of year
    NowMin=RTime(4)*60+RTime(5)
    If NowMin>=660 AND NowMin<780
      Modem=1
    Else
      Modem=0
    EndIf
    If BattV<11.5 Then
      Modem=0
    EndIf
    If Modem = 1 Then
      SW12(1)
    Else
      SW12(0)
    EndIf
    'Default Datalogger Battery Voltage measurement 'BattV'
    Battery(BattV)
    'Default Wiring Panel Temperature measurement 'PTemp_C'
    PanelTemp(PTemp_C,_50Hz)
    '03001 Wind Speed & Direction Sensor measurements 'WS_ms' and 'WindDir'
    PulseCount(WS_ms,1,1,1,1,0.75,0.2)
    If WS_ms<0.21 Then WS_ms=0
    BrHalf(WindDir,1,mV2500,1,1,1,2500,True,0,_50Hz,355,0)
    If WindDir>=360 Then WindDir=0
    'CS215 Temperature & Relative Humidity Sensor measurements 'AirTC' and 'RH'
    SDI12Recorder(TRHData(),7,"0","M!",1,0)

    'NR-LITE2 Net Radiometer (dynamic wind speed correction) measurement 'NR_Wm2' and
'CNR_Wm2'
```

```
VoltDiff(NR_Wm2,1,mv25,2,True,0,_50Hz,80,0)
If WS_ms>=5 Then
  CNR_Wm2=NR_Wm2*(1+0.021286*(WS_ms-5))
Else
  CNR_Wm2=NR_Wm2
EndIf

'SU-100 UV Sensor  measurements 'SlrMJ' and 'SlrW'
VoltSe(SlrUV,1,mV250,2,1,0,_50Hz,1,0)
If SlrUV<0 Then SlrUV=0
SlrUV = SlrUV * 6.54

'TE525/TE525WS Rain Gauge measurement 'Rain_mm'
PulseCount(Rain_mm,1,2,2,0,0.254,0)

'CS616 Water Content Reflectometer measurements 'VW' and 'PA_uS every 5 min'
If IfTime (0,5,Min) Then
  CS616(PA_uS,1,5,1,1,1,0)
  VW=-0.0663+(-0.0063*PA_uS)+(0.0007*PA_uS^2)
  'CS616 Water Content Reflectometer measurements 'VW_2' and 'PA_uS_2'
  CS616(PA_uS_2,1,6,2,1,1,0)
  VW_2=-0.0663+(-0.0063*PA_uS_2)+(0.0007*PA_uS_2^2)
  'CS616 Water Content Reflectometer measurements 'VW_3' and 'PA_uS_3'
  CS616(PA_uS_3,1,7,3,1,1,0)
  VW_3=-0.0663+(-0.0063*PA_uS_3)+(0.0007*PA_uS_3^2)
  'CS616 Water Content Reflectometer measurements 'VW_4' and 'PA_uS_4'
  CS616(PA_uS_4,1,8,4,1,1,0)
  VW_4=-0.0663+(-0.0063*PA_uS_4)+(0.0007*PA_uS_4^2)
  'CS616 Water Content Reflectometer measurements 'VW_5' and 'PA_uS_5'
  CS616(PA_uS_5,1,9,5,1,1,0)
  VW_5=-0.0663+(-0.0063*PA_uS_5)+(0.0007*PA_uS_5^2)
  'CS616 Water Content Reflectometer measurements 'VW_6' and 'PA_uS_6'
  CS616(PA_uS_6,1,10,6,1,1,0)
  VW_6=-0.0663+(-0.0063*PA_uS_6)+(0.0007*PA_uS_6^2)
  '107 Temperature Probe measurement 'T107_C'
EndIf

Therm107(T107_C,1,11,1,0,_50Hz,1,0)
'TE525/TE525WS Rain Gauge measurement 'Rain_mm_2'
PulseCount(Rain_mm_2,1,18,2,0,0.254,0)

'Code to switch SW12 on on power up of logger
'SW12 (1 ) Put in front of scan
'Code to switch SW12 of for one minute a minute after midnight to reset modem
```

```
    'If IfTime(1,1440,min)
    'SW12 (0 )
    'EndIf

    'If IfTime(2,1440,min) Then
    'SW12 (1 )
    'EndIf
    'End of code to switch SW12

    'Call Data Tables and Store Data
    CallTable(Five_min)
    CallTable(Hourly)
    CallTable(Daily)
  NextScan
EndProg
```