DETECTION AND ATTRIBUTION OF LONG-TERM CLIMATIC AND HYDROLOGICAL TRENDS IN THE CATHEDRAL PEAK CATCHMENTS

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Centre for Water Resources Research of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa. The research was financially supported by the Water Research Commission of South Africa.

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

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Dr Michele L. Toucher

DECLARATION

I, *Sibusisiwe Majozi*, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

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ABSTRACT

It has become accepted that global change is a considerable threat to vulnerable environments such as mountains. Various studies highlight the importance of change detection in long term climatic and hydrological data in understanding the catchment responses to various environmental changes. Long term trend detection of rainfall, temperature and streamflow has shown to be of practical importance to water resources management and planning. More especially in mountainous regions which have highly variable microclimates and are vulnerable to climate change impacts. In mountainous regions, the lack of data as a result of sparse observation networks often leads to a poor understanding of the climatic systems and amplifies the degree of uncertainty in trend detection. Given this need, the area of interest to this study was the intensively monitored Cathedral Peak catchments which are representative of the uKhahlamba Drakensberg region where a significant amount of water is generated for the KwaZulu-Natal and Gauteng provinces. In this context, the aim of the study was to detect trends in the historical hydroclimatic data of the Cathedral Peak catchments and gain understanding about the causes of change.

To accurately detect and attribute the hydroclimatic trends in rainfall, temperature and streamflow the study was carried out using three methods. The first method investigated the data for historical trends (1948 - 2000), followed by a comparative analysis which investigated the differences between the historical and current records (2012 – 2015). The third method was an attribution study which investigated the influence of rainfall and land use to determine which of the two considered factors contributed as the cause of change. The Mann-Kendall and Sen’s slope estimator non-parametric tests were used to detect trends in the data and determine magnitude of the trends detected while the Mann-Whitney test was used to detect the difference between the historical and current records.

The results across all times scales showed a few statistically significant trends in rainfall. However, the majority of the rainfall analyses showed no statistically significant trends with the expectation of a decline autumn rainfall detected in the seasonal analysis. The comparative analysis showed a few significant differences indicating increased rainfall between the historical and current period. The short current record was seen to have restrained the ability to detected definite differences in the rainfall.

The significant positive trends detected in the historical temperature records and the comparative analysis provided more evidence of an increase in the temperature between the historical and current period. Furthermore, the positive trends found in the daily maximum and average temperatures were consistent with those from previous studies, which can be used to establish that there has been a general increase in the temperature between 1955 and 2000. Significant negative trends were detected in both the historical streamflow and the comparative analysis which showed evidence of a distinct decline in streamflow between 1949 and 2000. The results from the attribution study indicated that both land use change and rainfall appear to have a noticeable impact on streamflow.

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 lack of significant trends detected from the historical records and the inconclusive results obtained from the comparative study. However, despite this shortfall detection and attribution studies remain a useful tool in providing valuable information on the effects of global change in sensitive and vulnerable environments such as mountains.

Keywords: Cathedral Peak, global change, mountainous areas, trend detection.

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1. INTRODUCTION

Change or trend detection procedures are undertaken to assess and evaluate the differences in an object or phenomena across time and space (Lu *et al*., 2004). From the 1950's, detection of historical changes in the climatic and hydrological variables has been emphasized in the research community (Frei and Schär, 2001; Molnár and Ramírez; 2001, Lu *et al*., 2004; Hamed, 2007; Ngongondo *et al*., 2011; Kalumba *et al*., 2013). Attention has been focussed on trend detection and analysis of rainfall, temperature and streamflow as they have been highlighted as key indicators of change in the hydrological cycle (Kundzewicz and Robson, 2000; 2004). Long-term trend detection, assessing historical hydrological and climatic variables, is of practical importance for the management of water resources particularly when planning for the potential impacts of climate change in addition to the uncertainties brought about by natural climate variability (Abdul Aziz and Burn, 2006; Beniston *et al*., 2014).

Human activities, such as deforestation and fossil fuel combustion, which emit greenhouse gases, continually alter the atmosphere composition thus changing the climate. Alteration of the concentrations of atmospheric gases leads to changes in the spatial and temporal distributions of rainfall, air temperature, potential evapotranspiration and other climatic variables, ultimately having a significant impact on the terrestrial hydrological cycle (Kundzewicz and Robson, 2000; Wu *et al*., 2014). The impacts of global climate change have been highlighted to cause considerable threats to vulnerable environments such as mountains (Farge, 2007). According to Kohler et al. (2014) mountainous regions have the ability to provide early warning signs of global change impacts as they are sensitive areas that have highly dynamic microclimates which also act as an indicator of change. The complex topography of mountainous areas is characterised by sharp changes in gradient, aspect and elevation which induce rapid changes in air temperature and precipitation, influencing the climate and subsequently the hydrology (Beniston *et al*., 1997; 2003).

The global scientific community has failed to see the importance of mountains regions and they are often perceived to have little or no influence on a global scale (Gautam *et al*., 2010). This, combined with the fact that mountain regions are remote and difficult to access has led to the lack of understanding of the climatic systems in mountainous regions due to the lack of long term data, which is the result of sparse observation networks found in such areas., (IPCC, 1995; Ward *et al*., 2011; Kao *et al*., 2013; Kattel and Yao, 2013). Extreme weather events, as a result of strong environmental gradients and spatial heterogeneity, enhance the difficulty of studying dynamic mountainous environments and add to the lack of understanding of weather patterns in these regions (IPCC, 1995; Farge, 2007; Kohler *et al*., 2014). Consequently, results from small, rural watersheds in developing countries are unnoticed and seen to add no value to global research (Gautam *et al*., 2010). These results are neglected because they are often inconclusive, consequently there is no general consensus on the observed changes and the trends in mountainous areas which may differ and not correlate with those trends observed for low lying lands (Gautam *et al*., 2010; Ward *et al*., 2011; Kao *et al*., 2013). Given this, a particular focus in researching and understanding these mountainous regions, which are sensitive to climate change, has emerged (Buytaert *et al*., 2006; Beniston *et al*., 2014). 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 change in average weather conditions over an extended period of time, attributed directly or indirectly to human activities and external forcing (Kundzewicz and Robson, 2000; IPCC, 2007; Gocic and Trajkovic, 2013). Burn and Hag Elnur (2002) and Kundzewicz and Robson (2004) note that change signals are not easily detected when the natural climate of an area is highly variable. Therefore, the highly variable climate of South Africa and mountainous regions Kalumba *et al*. (2013) may add complexity to detecting long-term trends in climatic and hydrological variables. The analysis of step or gradual changes in data allows for the distinction between natural variability or anomalies and long-term climatic and hydrological trends (Kundzewicz and Robson, 2000).

Numerous detection studies have been undertaken for areas where adequate data is available, mainly in developed countries (Beniston, 2006; Kingston *et al*., 2009; Guatum *et al*., 2010 Stahl *et al*., 2010; Sayemuzzaman and Jha, 2014), with studies in developing countries where data is not readily available being few (Ward *et al*., 2011; Ngongondo *et al*., 2011; Kao *et al*., 2013). Mountainous regions in southern Africa are a prime example of one such area, which is sensitive to climate change Buytaert *et al*. (2006) and where data is scarce, (McGuire *et al*., 2012).

South Africa (as a developing country) and more specifically the Cathedral Peak region as a small and pristine catchment face the impacts of both land use changes and global climate changes. The Cathedral Peak region is of value to this study as these are intensively monitored catchments and are representative of the eastern UKhahlamba Drakensberg escarpment, which is of enormous social, economic and environmental importance in South Africa, as a valuable and important source of runoff for Gauteng, KwaZulu-Natal and the surrounding rural community (Nel and Sunmer, 2006). In this context, understanding the hydroclimatic changes in the Cathedral Peak catchments as a representative area of a high altitude region is of crucial importance for planning and managing South Africa's water resources.

The lack of reliable long-term historical data as a result of the complex terrain and sparse observation network has restrained trend detection studies in mountainous regions, with the majority of studies focused on temporal and spatial variability of climatic variables. Thus no general consensus has been established on the hydroclimatic changes in high altitude areas. In the effort to gather much needed information and understanding on global change impacts, the reestablishment of intensive monitoring and the available long term historical records from the Cathedral Peak research catchments have provided the opportunity to begin to conduct detailed studies on hydroclimatic changes in the Cathedral Peak region.

The broad objective of this study was to examine temperature, rainfall and streamflow data of the Cathedral Peak catchments in order to detect trends in the climatic and hydrological variables and thereafter attribute the causes of change. The aims under this broad objective were to:

- Detect trends and changes in the temperature, rainfall and streamflow historical records from the Cathedral Peak catchments,
- Detect changes and any noticeable differences between the current and historical temperature, rainfall and streamflow records.
- Determine if these trends correlate with those observed at national scale.
- Investigate possible causes and explanations for the changes detected.

Following this introduction, Chapter 2 partly addresses the third aim through a literature review that highlights the hydroclimatic trends that have been observed in previous studies with a focus on southern Africa and mountainous areas. Chapter 3 provides detail of the methodology followed. Chapter 4 presents the results obtained from the detection study of the temperature, rainfall and streamflow records while Chapter 5 addresses attribution of the observed trends. A discussion of the study in Chapter 6 highlights whether the results of the detection study correlate with national trends reviewed in the literature. Recommendations for future research are provided in Chapter 7.

2. LITERATURE REVIEW

Increased awareness of the potential impacts of climate change has focused attention on the importance of long-term trend detection of climatic and hydrological parameters such as rainfall, temperature and streamflow, recognizing them as key indicators of change (Burn and Hag Elnur, 2002). A key question presented in the literature was to understand the changes in the hydrological cycle by assessing long-term data to determine whether these changes are attributable to climate change or natural variability (Kundzewizc and Robson 2000). Rainfall and temperature have often been the primary variables used in change detection studies as they are the drivers of the hydrologic and climatic systems (Kundzewizc and Robson 2000; Li *et al*., 2011; Nguyen *et al*., 2014). Changes in both temperature and rainfall are often noticeable through changes in streamflow regimes (Thorne and Woo, 2011), as well as extreme events such as floods and droughts (Easterling *et al*., 2000). The main constraints in trend detection studies have been the lack of long-term data and the uncertainty introduced by climate variability, despite these challenges a number of studies globally have been conducted (Kundzewizc and Robson 2000; Burn and Hag, 2002; Ward *et al*., 2011; IPCC, 2013; Kao *et al*., 2013). A review of temperature, rainfall and streamflow detection studies was undertaken prior to the detection study for the Cathedral Peak region to determine the most suitable statistical methods to use and to be able to compare the results obtained for the region to those found in other studies.

2.1 Trends in Temperature

Atmospheric and climatic changes are mostly detected by variations in the temperature (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).

2.1.1 Global and continental scale trends in temperature

Globally, trends in temperature 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°C from the mid-century (Easterling *et al*., 2000; Zhang *et al*., 2000; Feidas *et al*., 2004; Mohsin and Gough, 2010; Kruger and Sekele, 2013; IPCC, 2013). Of the global land surface area, 74% shows a positive trend in minimum temperature, extreme minimum temperatures and a decreasing diurnal temperature range (Zhang *et al*., 2000; Mohsin and Gough, 2010 Kruger and Sekele, 2013).

Various studies undertaken in different parts of the world have begun to display warming trends indicative of climate change. In the Northeastern United States, seven out of nine states displayed significant warming trends between 1900 and 2011 (Karmeshu, 2012). A study considering temperature extremes in Europe and China found that since 1961, strong increases in warm extremes and decreases in cold extremes have accompanied a gradual, strong warming trend (Yan *et al*., 2002). In Athens, Greece the maximum temperature was found to have increased by 2°C between 1925 and 1996 while no significant trends were found in minimum temperatures (Philandras *et al*., 1999). Temperature studies by Aesawy and Hasanean (1998) for the southern Mediterranean found significant positive annual trends for all the stations and persistent positive trends in the summer and autumn temperatures. In the city of Ankara, Turkey positive temperature trends were found for all seasons (Cicek and Dogan, 2006).

Trends in global temperature are greatest and most significant in high altitude regions with increases observed in daily minimum temperatures but not in maximum temperatures (Rangwala and Miller, 2010; McGuire *et al*., 2012) and a negative trend in the diurnal temperature range. Kattel and Yoa (2013) found similar trends in the annual temperatures as well as the diurnal temperature range 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 of approximately 1°C between 1895 – 2005, with a more rapid increase in the last 20 years as well as evidence of a decreasing diurnal temperature trend. These observations show evidence and further support that mountainous regions are more sensitive to climate change impacts than low lying areas or regions in low altitudes. The majority of high altitude temperature studies are conducted in the northern hemisphere with few studies emerging from the southern hemisphere and even fewer from African countries. The following section focuses on those studies from southern Africa.

2.1.2 Temperature trends across southern Africa

Similar warming trends to those observed at a global scale and across the southern hemisphere have been shown by Hulme (1996); Mason and Jury (1997); Kruger and Shongwe (2004); New *et al.* (2006) and Kruger and Sekele (2013) for southern Africa. According to Jury (2013), temperatures across southern Africa have increased significantly at a rate of 0.03 °C/year since 1960 in some places. Stronger warming trends have been noted in the western parts of South Africa (Mason and Jury, 1997). Kruger and Sekele (2013) indicate positive trends 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 indicating a decrease in the diurnal range. Regional studies tend to agree with the national level results (Kruger and Shongwe, 2004; Tshiala *et al.*, 2011). For example, an increasing trend of 0.12^{o}C in the average annual temperature of 30 catchments in Limpopo for the period 1950-1999 was found by Tshiala *et al.* (2011), as well as statistically significant positive trends in average annual maximum and minimum temperatures. Positive trends in the diurnal temperature range were observed for 80% of the catchments while 20% showed negative trends (Tshiala *et al.*, 2011).

Although, temperature detection studies have been conducted in South Africa, there is still a lack of focus on mountainous regions primarily due to a lack of data, however, these mountainous areas are vulnerable and potentially severely affected by changes in temperature according to global studies. The reported increases in surface air temperatures have left little doubt that global change may have direct and indirect impacts on water resources management (Jhajharia *et al.*, 2013; Sonali and Kumar, 2013; Tshiala *et al.*, 2011) through a change in rainfall, as reviewed below, and evaporation.

2.2 Trends in Rainfall

Precipitation is a principal element in the hydrological cycle (Easterling *et al.*, 2000; Buytaert *et al.*, 2006; Duhan and Panday, 2013). It is largely determined by atmospheric and meteorological factors and in turn is the main driver of the hydrological cycle (Ogutunde *et al.*, 2011). Rainfall is the main determinant of agricultural production, economic activity, social wellbeing and environmental health (Shahid, 2011; Ward *et al.*, 2011; Duhan and

Pandey, 2013; Ahammed *et al*., 2014; Sayemuzzaman and Jha, 2014). As a result, changes in precipitation distribution, amounts and variability greatly affect water resources management, industry, human health and ecosystem goods and services (Ogutunde *et al*., 2011; Shahid, 2011; Yavuz and Erdoğan, 2011; Duhan and Pandey, 2013). Therefore, an understanding of the long-term spatial and temporal variations of rainfall is important in the development of strategies to reduce vulnerability (Oguntunde *et al*., 2011; Yavuz and Erdoğan, 2011; Guaghan and Waylen, 2012; Koa *et al*., 2013; Nsubuga *et al*., 2014).

2.2.1 Global and continental scale trends in rainfall

Observed trends in rainfall patterns are not uniform across the world (Burn and Hag Elnur, 2002; Kalumba *et al*., 2013). Traditionally, rainfall detection studies have focussed on changes in rainfall depth such as the mean monthly, seasonal and annual amounts (Easterling, 2000; Frei and Schär, 2001). However, recent studies show that components such as rainfall intensity, event frequency (Shahid, 2011) and shifts in rainfall patterns (Karl and Knight, 1998); New *et al*. (2006); Shahid (2011) have become of interest. This is because the early signs of climate change impacts have begun to show increases in heavy and extreme rainfall events and projections of future climate scenarios have predicted that increases in rainfall variability and extreme events.

On a global scale annual precipitation changes show parts of the world experiencing more rainfall and others less (Figure 2.1; IPCC, 2013). The changes observed prior to 1951 are noticeably lower than those observed after 1951. Furthermore, the IPCC (2013) reports that confidence in rainfall changes in the last 60 years is far greater than the period before 1951 meaning that the changes in precipitation are more likely to have occurred or become more pronounced after 1950 as a result of increased external human forcing which are the human impacts or the effects of human activities on the atmosphere and environment.

According to New *et al*. (2006) and Sayemuzzaman and Jha (2014), observed trends across the United States show increases in rainfall over the past decades. Karl and Knight (1998) found a 10% increase in annual precipitation across the United States between 1910 and 1996. Similarly, Groisman *et al*. (2012) reported increases of 6% in heavy precipitation during the past century across the United States and statistically significant increases in extremely heavy precipitation over the past 30 - 40 years in Central America.

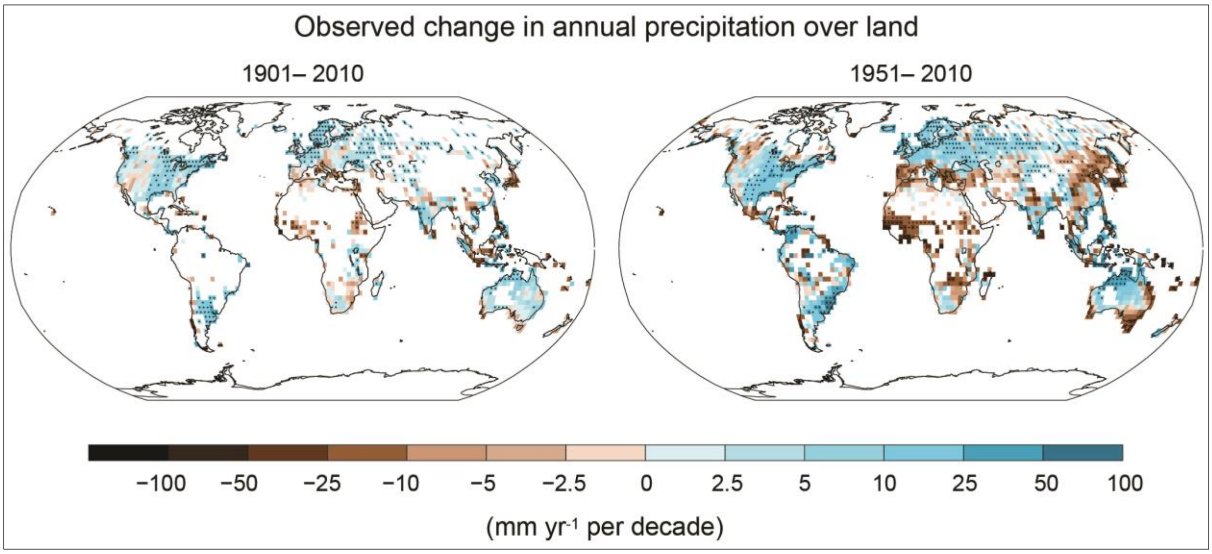

Figure 2.1: Observed precipitation changes from 1901 to 2010 and from 1951 to 2010 (IPCC, 2013)

Rainfall changes across Australia are influenced by increased sea surface temperatures as a result of the El Niño Southern Oscillation, changes in monsoon troughs and anthropogenic activities (Lavender and Abbs, 2013). 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 Australia, Barua *et al*. (2013) showed a decreasing trend in annual rainfall 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 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).

The above studies have considered global and continental rainfall trends at different spatial scales and some have included mountainous regions. However, the significance of trends in several mountainous regions is unknown because of a lack of long-term data as a result of sparse observation networks due to complex terrain (Haile *et al.*, 2009; Kao *et al.*, 2013). Mountainous regions are difficult to access due to their remoteness and complex terrain which results in sparse observation networks and consequently leads to the lack of data available to conduct in-depth studies.

From the literature reviewed, it was noted that few rainfall detection studies have been undertaken in developing countries as data is not readily available. For Africa, the majority of detection studies that have been undertaken are for southern Africa.

2.2.2 Rainfall trends across southern Africa

Southern Africa is a water-scare region characterised by a semi-arid, sub-humid climate with a complex rainfall regime that is highly sensitive to rainfall shifts and variability (Nicholson, 2000; Gaughan and Waylen, 2012). In many southern African countries trend detection studies of hydrological and climatic variables have been, and are still, limited by the lack of long term data (New *et al.*, 2006). Despite the lack of data, starting from the 1950's, there has been an increase in research which focuses on the trends and variations in temperature and rainfall of southern Africa (Nicholson, 2000).

In one of the earliest trend detection studies for Africa, Hulme (1992) showed no significant trends in southern African rainfall between the periods 1931-1960 and 1961-1990. However, a later study by New *et al*. (2006) reported a general negative trend in southern African rainfall since 1961. Studies conducted at regional scales confirm a decreasing trend but vary in magnitude. Guaghan and Waylen (2012) showed a negative trend in the rainfall patterns between 1950-1975 and 1980-2005 for the Okavango-Kwando-Zambezi catchment. For Malawi, negative monthly rainfall trends were detected between 1960 and 2006 at 88% of the stations analysed, however the trends were only statistically significant at four stations. 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 decreasing rainfall trends for Zimbabwe and Zambia. Hulme *et al*. (1996) and Gondwe *et al*. (1997) found a

10% decrease 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 show 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 Africa, Mason and Jury (1997) reported a decrease in mean annual rainfall for the eastern lowveld, as well as an increasing trend in rainfall variability. Similarly, Kalumba *et al*. (2013) showed increasing inter-annual rainfall variability across South Africa. Mason *et al*. (1999) showed significant increases in rainfall and extreme events between 1931-1960 and 1961-1990.

South Africa's rainfall varies with altitude from a mean annual precipitation (MAP) of 250 mm at low altitudes to a peak MAP of 2 000 mm at the top of the Drakensberg escarpment where altitude is approximately 2800 – 3000 m above sea level (Nel and Sunmer, 2006). The influence of slope, aspect and altitude on rainfall patterns in mountainous regions is highlighted in studies by Buytaert *et al*. (2006), Nel and Sunmer (2006), Haile *et al*. (2009), Nel (2009) and Kao *et al*. (2013). In addition to this, Nel and Sunmer (2006) and Nel (2009) considered the seasonal and inter-annual variability of rainfall finding no evidence of rainfall trends for the Drakensberg area between 1921 and 2000. However, no studies have comprehensively assessed long-term trends in high altitude rainfall records.

Temporal and spatial rainfall variability across South Africa and southern Africa is well documented in the literature with a few studies reporting on trends in the region, however, those detection studies undertaken agree that rainfall across southern Africa is decreasing. The difficulties associated with detection studies in developing countries are evident with none of these reviewed studies considering mountainous areas specifically because of a lack of long-term data as a result of sparse observation network due to complex terrain (Buytaert *et al*., 2006; Haile *et al*., 2009: Kao *et al*., 2013). Although trends in rainfall may not be evident, due to the amplification of changes in rainfall through the hydrological cycle and the influence of temperature on evaporation, discrete changes in rainfall are often more noticeable in streamflow (Molnar and Ramirez, 2001; Thorne-Woo, 2011).

2.3 Trends in Streamflow

Streamflow observations have received increased attention over the past decades (Stahl *et al*., 2010). 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. Furthermore, they reflect the spatially integrated response of the catchment as a single unit (Burn and Hag Elnur, 2002). Attribution studies analyse and interpret results with the objective to explain and account for to the changes detected in the environment. 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-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).

2.3.1 Global and continental scale trends in streamflow

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 over 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°C temperature increase in parts of North and South America. This is as a result of global warming coupled with the intensification of the global hydrological cycle and increased continental precipitation leading to increased continental runoff (Labat *et al*., 2004).

At a continental scale, Milly *et al*. (2005) and Stahl *et al*. (2010) showed positive trends in annual streamflow in the northern parts of Europe and negative trends for the southwest and eastern parts. Furthermore, monthly trends in Europe reveal greater temporal detail showing positive trends in the winter months between October and March and negative trends or no trends for the remainder of the year while positive trends in the low flows in the winter months and negative trends in the summer months were also evident (Stahl *et al*., 2010; Kingston *et al*., 2009). The decrease in low flows during the summer months is as a result of snowmelt occurring later in the season thus contributing to streamflow during the dry period when low flows are expected to increase (Kingston *et al*., 2009).

A number of streamflow studies have been conducted at a continental scale in the northern hemisphere particularly focussing on snow-fed mountainous regions in developed countries (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 a 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). Despite these advances, few studies have been conducted in Africa and South Africa, and even fewer in the mountainous areas of these regions.

2.3.2 Streamflow trends across southern Africa

Observed streamflow trends for southern Africa revealed increased variability from 320 $mm.yr^{-1}$ in the lower Zambezi and Tanzania to less than 10 $mm.yr^{-1}$ in Namibia and the Kalahari (Fanta *et al*., 2001). Sene *et al*. (1998) found evidence of a strong relationship between rainfall and streamflow in Lesotho on an annual basis, however, similar to other studies conducted in southern Africa, no significant long-term trends were detected. 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 with the remaining 269 stations showing no trends. The conclusions drawn from this study suggest that on a continental scale, there has been an observed decline in mean annual runoff commencing from 1975. This is further supported at a regional scale with similar trends observed for Zambia, Mozambique, Angola and the High Veld in South Africa (Fanta *et al*., 2001).

Odiyo *et al*. (2011) examined the relationship between rainfall and streamflow in the Luvuvhu River catchment, South Africa using the 5 and 10 year means from 1931 - 2006 and revealed increasing variability in both rainfall and streamflow. The 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 are not consistent with the rainfall trends. This inconsistency can be attributed to other confounding factors as a result of anthropogenic activities such as impoundments and urban development which increase streamflow (Odiyo *et al*., 2011).

The literature reviewed in this section demonstrates that there has been 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 of streamflow trends, particularly in mountainous areas which contribute significantly to streamflow and inevitably affect water resources management and planning (Westmacott and Burn, 1997; Kingston *et al*., 2009; Stahl *et al*., 2010; Abghari *et al*., 2013).

2.4 Discussion

According to the Beniston and Stoffel (2014) under Agenda 21 of the UNCED conference mountainous regions were included and highlighted as key indicators of environmental change, because the physical and biological systems in such areas are seen to display characteristics that are often more easily noticed than in other geographical entities of the globe.

Guatam *et al*. (2010) states that trends of hydroclimatic variables in small, rural, non-snow-fed mountainous watersheds in developing countries have so far mostly been thought of as local issues with little impact to global communities. However, this perception is not always true with the literature highlighting the importance of such regions in the provision of early warning signals for global climate change. Given this, Rangwala and Miller (2010) and McGuire *et al*. (2012) have indicated that mountainous climates have become the focus in recent climate change research, which highlights the increased awareness in the scientific community. This draws attention to the importance of this study as it adds to the existing knowledge of hydroclimatic trends and climate change impacts in mountainous regions.

The lack of observation stations, insufficient long-term historical records and complex terrain are common difficulties associated with quantification of long-term trends in mountainous regions (Ward *et al*., 2011; Kattel and Yao, 2013; Kao *et al*., 2013) and result in a lack of reporting on hydroclimatic variables and trends in these variables for high altitude areas. Despite these challenges, it is crucial to understand the sensitivity and responses of mountainous regions to global change. To achieve this, detection of trends in long-term historical records is critical as well as determining the cause of these changes (Buytaert *et al*., 2006). In this context, understanding changes in the hydroclimatic regime in the Cathedral Peak catchments as a representative area of the eastern uKhahlamba Drakensberg is of crucial importance for planning and managing South Africa’s water resources.

3. METHODOLOGY

The methodology followed to determine whether trends in rainfall, temperature and streamflow are evident in the Cathedral Peak region comprised of three main stages, namely data quality control and visual analysis, application of statistical tests and lastly interpretation of trends. Data quality control is an essential component and includes obtaining and preparing the data in order to compile a suitable dataset for analysis (Easterling *et al.*, 2000; Kundzewicz and Robson, 2004; Shahid, 2011). During this stage, it is important to consider the record length, time step of the data and missing data values in order to compile a complete record for statistical analysis (Kundzewicz and Robson, 2004). Record length is a recurring challenge in detection studies (Dixon *et al.*, 2006). Dixon *et al.* (2006) has shown that hydrological related statistically significant trends are better or more easily detected in longer record lengths as opposed to shorter record lengths. Burn and Hag Elnur (2002) suggest a minimum record length of 25 years, while Kunzdewicz and Robson (2000) and Dixon *et al.* (2006) advocate for the use of the longest data record available to ensure the detection of any statistically significant trends and avoid false detection of trends. The importance of a record length is emphasized when data which is naturally variable or has persistent weather patterns such as the El Niño Southern Oscillation is analysed. Prior to describing the procedures followed in this study, the Cathedral Peak region is described.

3.1 Study Site Description: Cathedral Peak region

The study site was the intensively monitored Cathedral Peak research catchments (29° 00' S, 29° 15' E) on the Little Berg plateau located below the escarpment of the UKhahlamba Drakensberg mountain range, KwaZulu-Natal, South Africa (Figure 3.1). The Cathedral Peak research catchments are made up of fifteen subcatchments which have a total area of 11.14 km^2 and an altitudinal range of 1845 – 2454 m a.s.l (Scott *et al.*, 2000). The catchments are situated in a summer rainfall region and with a MAP ranging between 1300 – 1400 mm. Approximately 80 - 85% of the rainfall occurs between October to March (inclusive), 50% of the rainfall results from thunderstorm activity, and 45 – 50% of the rainfall is converted into runoff (Scott *et al.*, 2000, Govender and Everson, 2005). The catchments also receive occasional snowfall in winter (Scott *et al.*, 2000, Govender and Everson, 2005).

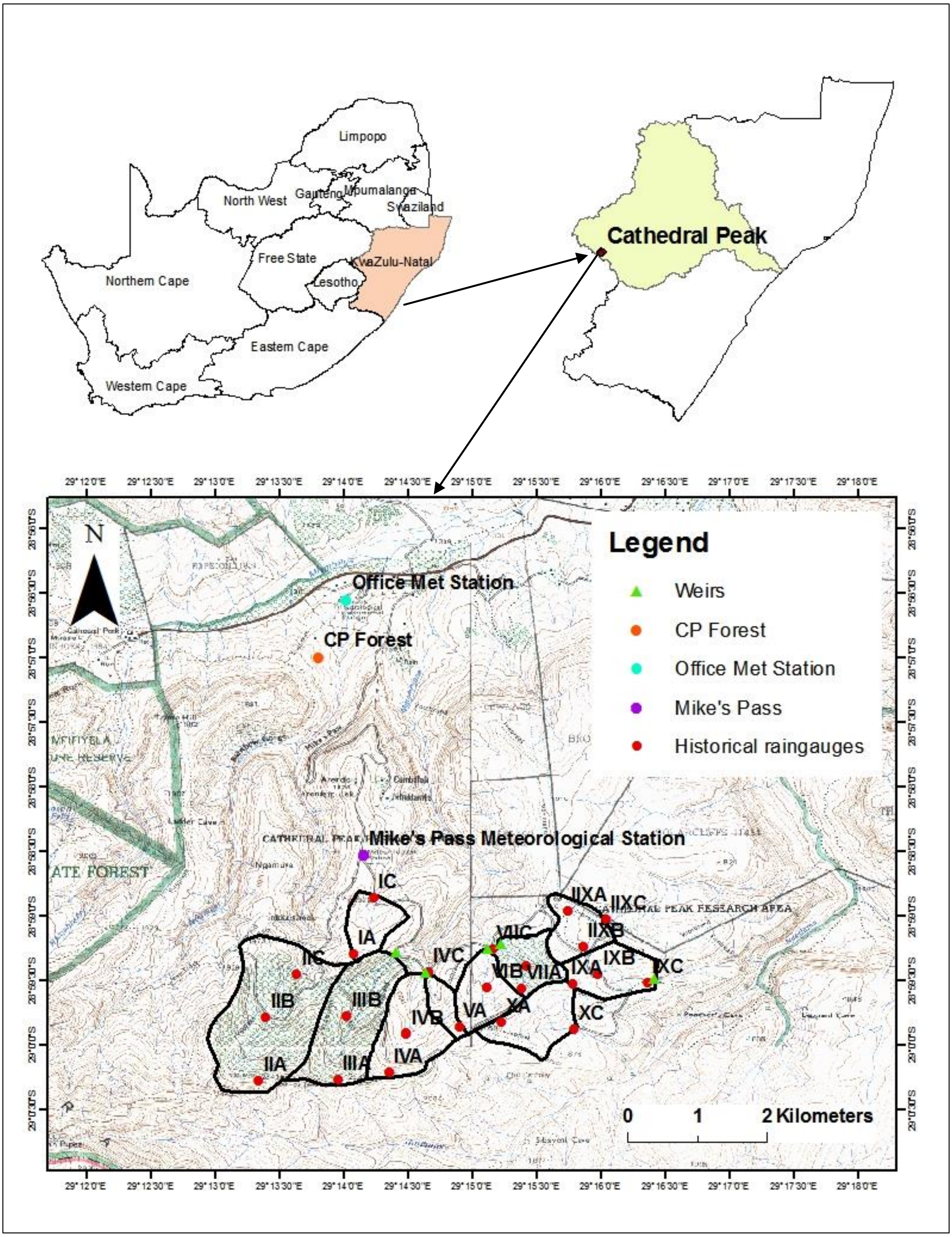

Figure 3.1: Location of the Cathedral Peak research catchments, the meteorological stations, weirs and raingauges within the catchments.

Historically, meteorological variables were monitored at two primary weather stations one located at Mikes Pass meteorological station (referred to as Mike's Pass station in this document) and the other located near the research office. Recording at Mike's Pass started in 1949 and continued to 1994. While for the station located near the research office monitoring was initiated in 1952 and continued till 1993. Recording was done manually until 1984 when automated weather stations were introduced.

In addition to the weather stations, rainfall was historically monitored at 25 raingauges installed across Catchments I – X for various time periods during the years 1948 - 1994. Streamflow was monitored for all catchments with gauging weirs installed at the outlet of each catchment at different stages starting with Catchments I – IX during the late 1940's and 1950's, followed by Catchment X during the 1960's and in the 1970's Catchments XI – XV. Beyond the variables considered for the study, other variables have been monitored in the catchments including evaporation and groundwater. Due to a lack of funding all monitoring in the catchments was discontinued in 1994/1995.

In 2012, monitoring resumed in the catchments due to a South African Earth Observatory Network (SAEON) initiative. To date, monitoring has been re-established at the Mike's Pass meteorological station, the meteorological station near the research office, at 24 raingauge sites and weirs IV, V, VI and VII. The meteorological stations, rainfall gauges and streamflow gauges have been upgraded to modern equipment. More details on the rainfall, temperature and streamflow data are provided below.

3.2 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 accurate detection of trends in the data (Kundzewicz and Robson, 2004). The rainfall data used for this study was sourced from SAEON from two separate time periods *viz,* a historical time period from 1948 –1994 and a current time period from 2013 to present. Table 3.1 provides details on the start and end dates, time steps and the length of both the historical and current rainfall records. The historical rainfall dataset was assessed for inaccuracies and was found to contain errors and missing values, therefore it was patched as described below. The current daily rainfall data was complete with no inaccuracies or missing values and thus did not need to be patched.

Table 3.1: Details of the historical and current rainfall data sourced from South African Environmental Observation Network (SAEON).

Raingauge	**Historical Rainfall Record**				**Current Rainfall records**			
	Start date	**End date**	**Length (yrs)**	**Time Step**	**Start date**	**End date**	**Length (mnths)**	**Time Step**
IA	Aug 1950	Sep 1985	35	Monthly	No data			
IC	No data				Nov 2013	July 2015	20	Daily
IIA	Aug 1948	Feb 1993	45	Monthly	Nov 2013	July 2015	20	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	20	Daily
IIIA	Aug 1950	Oct 1990	40	Daily	Nov 2013	July 2015	20	Daily
IIIB	Jan 1990	Oct 1990	0	Monthly	Nov 2013	July 2015	20	Daily
IVA	Jan 1949	Dec 1987	38	Daily	Sep 2013	July 2015	22	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	20	Daily
VIIC	Aug 1980	Aug 1990	10	Monthly	Sep 2013	July 2015	22	Daily
VIIIA	Oct 1965	Feb 1993	28	Monthly	Nov 2013	July 2015	20	Daily
VIIIC	Oct 1965	Feb 1993	28	Monthly	Nov 2013	July 2015	20	Daily
IXA	Jun 1954	Mar 1989	35	Monthly	Nov 2013	July 2015	20	Daily
IXB	Jun 1954	Mar 1989	35	Monthly	Nov 2013	July 2015	20	Daily
IXC	Oct 1985	Jul 1990	5	Monthly	Nov 2013	July 2015	20	Daily
XA	July 1955	Feb 1993	38	Monthly	Jan 2014	July 2015	18	Daily
XB	Mar 1973	Sep 1985	12	Monthly	No Data			
XC	July 1955	Sep 1985	30	Monthly	Dec 2013	July 2015	19	Monthly
Mike's Pass	Nov 1948	Mar 1984	36	Monthly	Nov 2012	July 2015	20	Daily
Office Met	Oct 1972	Feb 1993	21	Monthly	No Data			

To ensure the longest record length possible was used, as recommended by Dixon *et al.* (2006) and Kunzdewicz and Robson (2004), five patching methods were investigated for possible use to achieve complete historical rainfall datasets. The patching methods considered have been extensively investigated by Bennet *et al*. (2008) and are described as simple and computationally inexpensive. The patching techniques were the Nearest Neighbour by Distance (ND), Nearest Neighbour by Correlation (NC), Inverse Distance Weighted (IDW), Average (A) and a Weighted Average (WA).

The nearest neighbour by distance method uses the closest raingauge to estimate the missing rainfall data. ArcGIS with the geographical point locations of the historical raingauges was used to determine the distance (m) from the reference raingauge to the nearest raingauge.

The nearest neighbour by correlation method uses the raingauge with the highest correlation to estimate the missing data for the reference gauge. A correlation analysis between the raingauges allowed for the selection to be undertaken. The raingauge with the highest correlation was selected.

The IDW method uses multiple neighbouring gauges weighted by distance. In this study the three nearest raingauges were used to estimate rainfall for the reference gauge (P_c).

$$\boldsymbol{P_c = \Sigma\, P_i {d_{ci}}^{-k} / \Sigma\ {d_{ci}}^{-k}} \tag{3.1}$$

where,

P_c= the rainfall for the gauge to be patched

P_i= a neighbouring gauge

d_{ci}= the distance between the gauges

k = a weight known as the friction distance

For the Average of Gauges Selected by Correlation (A), the average daily rainfall is estimated using the average rainfall from three raingauges with the three largest correlations (correlation must be larger than 0.7).

While the Weighted Average of Gauges Selected by Correlation (WA) method selects gauges with the three largest correlations. The daily rainfall for each raingauge are averaged weighted by the correlation level.

Once the rainfall infilling was complete the performance of all the methods was assessed using three error statistics (Table 3.2). The error statistics used were the root mean square error (RMSE), mean bias, Nash–Sutcliffe model efficiency coefficient (NSE) and correlation (CORREL). The results from error testing showed that the IDW method produced the least error when compared to the other patching methods hence, it was selected as the best patching method. Examination of the historical data showed that a majority of the raingauges recorded data on a monthly time step. Thus the historical data used in this study was patched at a monthly time scale using IDW and a combination of the patching was used to produce a twenty year dataset (1965 – 1985) on which the statistical tests were applied. This work was conducted in collaboration with Morris *et al*. (2015).

Table 3.2: Error statistics results from patching methods

	RMSE ERROR		**MEAN BIAS (mm)**		**NSE**		**CORREL**	
	VIB	**VIIA**	**VIB**	**VIIA**	**VIB**	**VIIA**	**VIB**	**VIIA**
ND	3.526	4.296	-0.337	-0.496	0.774	0.66	0.901	0.859
NC	3.535	4.296	-0.434	-0.485	0.758	0.662	0.901	0.859
IDW	1.716	1.991	0.164	0.033	0.943	0.923	0.973	0.962
WA	10.622	9.68	4.005	3.089	0.632	0.613	0.941	0.867
A	2.593	3.605	0.015	-0.188	0.891	0.774	0.947	0.897

3.3 Temperature Data Acquisition

Given that the historical temperature data was only available for the Mike's Pass meteorological station (1955 - 1984) and the meteorological station located at the research office (1972 - 1993) from SAEON, ten additional temperature stations within a 60 km radius of the Cathedral Peak catchments were 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 site (0299417 A), was suitable for analysis as it contained more than 80% observed data for the period 1970-2000. Thus, the historical temperature trend analysis was undertaken using data from three stations.

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

3.4 Streamflow Modelling and Record Length Extension

Daily streamflow data for a historical period and a current period was obtained from SAEON for the weirs located at the outlets of Catchments IV, VI and VII, as well as III and IX for the historical period. Table 3.3 provides details of the historical and current streamflow data obtained. The historical streamflow record was assessed for inaccuracies and found to contain errors and missing values, and therefore needed to be patched. Streamflow modelling was carried out to extend the length of the records and patch where necessary. Prior to the streamflow modelling, the existing historical rainfall records for each catchment were extended using rainfall data from the Cathedral Peak Hotel and the linear regression method. The Cathedral Peak Hotel rainfall data was used to extend the records because it was longer (1882-01-01 to 2000-08-31) thus, it could be used to simulate streamflow for a longer period. Thereafter, streamflow modelling was conducted using the newly extended rainfall data and the ACRU model (Figure 3.2).

Table 3.3: Historical and current streamflow data record sourced from South African Environmental Observation Network (SAEON)

	Historical streamflow records			**Current streamflow records**		
	Start date	**End date**	**Length (yrs)**	**Start date**	**End date**	**Length (months)**
III	May 1952	Oct 1991	39	No data		
IV	Jan 1949	Dec 1987	38	Apr 2014	Dec 2015	20
VI	Jan 1960	April 1997	37	Feb 2014	Dec 2015	22
VII	Jan 1957	Feb 1993	36	Feb 2014	Dec 2015	22
IX	Oct 1954	Mar 1989	35	No data		

3.4.1 Conceptualization of the ACRU model

The ACRU model, developed at the University of KwaZulu-Natal, is daily time step, multi-purpose, multi-level agrohydrological simulation model (Ghile and Schulze, 2008). It is a physical conceptual model in the sense that the input parameters are estimated from physical characteristics of the catchment. The model was selected for this study because it has been widely used in a number of studies across Southern Africa (cf. reviews by Schulze, 1995; Schulze and Smithers, 2004) and elsewhere in the world (e.g. Dunsmore *et al*., 1986; Ghile, 2004). The ACRU model is a versatile total evaporation model structured to be sensitive to the climate, land cover and land use management changes on the soil water and runoff regimes (Schulze, 2008; Schulze and Pike, 2008, Warburton, 2010). ACRU operates as a point or lumped model, ranging from small to large catchments up to 400 km^2 to simulate the components and processes of the hydrological cycle affected by the soil-water budget, such as stormflow, baseflow, irrigation demand, sediment yield or crop yield, and to output any of those components on a daily basis (where applicable), or as monthly and annual totals of the daily values (Ghile and Schulze, 2008; Warburton *et al*., 2010).

The hydrological cycle is conceptualised as shown in Figure 3.2 in the ACRU model. The model operates on a multi-layer soil water budget which partitions and redistributes soil water in the terrestrial hydrological system (Schulze, 2008; Schulze and Pike, 2008). The model considers rainfall or irrigation as inputs to the system which, if not initially abstracted as interception or later as stormflow, first enters the top soil horizon (Schulze and Pike, 2008; Warburton, 2012). The movement of water in the model revolves around a surface layer and two soil horizons, *viz.* the top soil and subsoil (Ghile and Schulze, 2008; Schulze and Pike, 2008). Total evaporation is made up of both evaporation from the soil surface (E_s) and evaporation from a vegetated surface transpiration (E_t) which is governed by the active roots in the topsoil (Schulze and Pike, 2008, Warburton *et al*., 2010). Soil water evaporation and transpiration can either be modelled jointly or separately. Extraction of soil water occurs through soil water evaporation and transpiration from the top soil and capillary action from the subsoil while other water losses occur from runoff and saturated drainage. Once the topsoil is saturated beyond capacity the water percolates into subsoil horizons (Schulze and Pike, 2008; Warburton *et al*., 2010; 2012). If the subsoil horizons reach capacity the water continues to move through the soil and becomes ground water which at a later stage may contribute to baseflow. Unsaturated soil water moves at a slower rate and water movement is dependent on antecedent soil moisture and the relative wetness of adjacent soils (Ghile and Schulze, 2008; Schulze and Pike, 2008).

The average monthly crop coefficient (CAY) is the water use coefficient used to estimate vegetation water use within the ACRU model. The water use coefficient describes the transpiration and soil water losses to the atmosphere under sufficient soil water conditions. It is expressed as the ratio of maximum evaporation to a reference potential evaporation. It is determined by the plants actively photosynthesising biomass and is therefore influenced by the structure, reflectivity of solar radiation, aerodynamic roughness, growing season, spacing and covering. During periods of sustained plant stress, when the soil water content of both the upper and lower soil horizons is lower than 40% of plant available water, transpiration losses are reduced in proportion to the level of plant stress. When plant available water exceeds 40% in either soil horizon the plant stress is relieved and the evaporative losses return to the optimum value at a rate dependent on the ambient temperature (Schulze and Pike, 2008; Warburton, 2012).

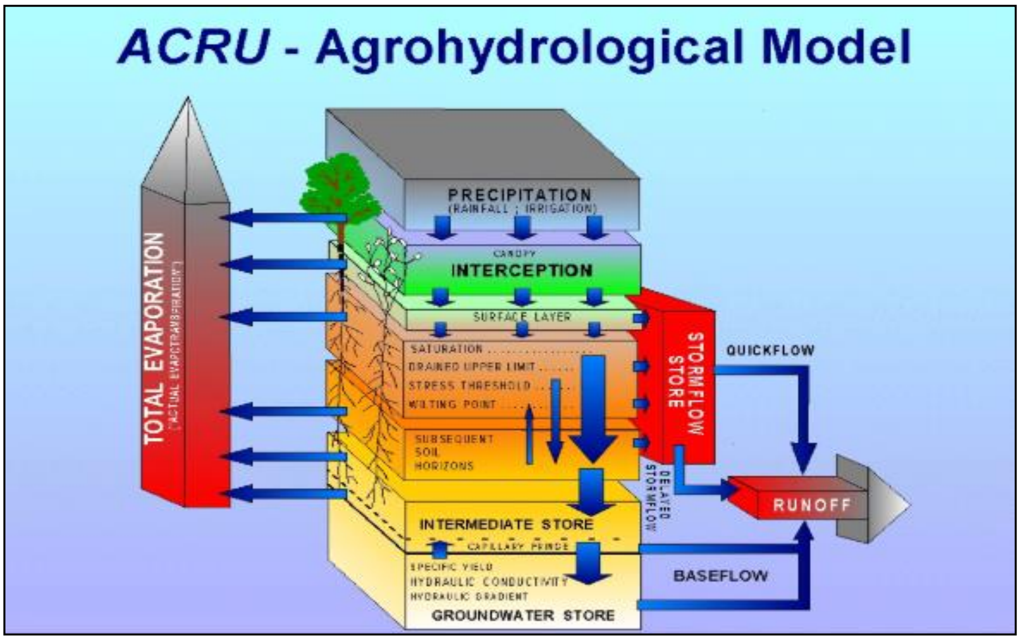

Figure 3.2: Conceptualization of the water budget in the ACRU model (Schulze, 1995)

The vegetation is expressed using hydrological variables which consider above, ground and below surface attributes that best describe the land cover (Schulze and Pike, 2008). The canopy interception per rainday for a specific crop (VEGINT) is a function of the leaf area index (LAI) and the rainfall, which together are used to estimate the evaporation from a vegetated surface. The estimation of canopy interception accounts for inter-annual variability in the growing season such as growth stage and dormancy. The values for interception loss range from zero for freshly ploughed land (bare soils) up to 3.5 mm per rainday for mature trees grown for commercial forestry (Schulze and Pike, 2008; Warburton, 2012). The fraction of active root mass found in the topsoil (ROOTA) represents the simultaneous extraction of soil water from both soil horizons, by proportionally distributing the active roots within each horizon (Warburton *et al.,* 2010). The values for ROOTA consider genetic and environmental factors affecting transpiration such as growth in the spring and dormancy in winter (Schulze and Pike, 2008; Warburton *et al.*, 2010; 2012). The coefficient of initial abstraction on a given rainday (COIAM) is the rainfall abstracted as interception, surface storage and infiltration from which thereafter stormflow is generated. Initial abstractions are dependent on the antecedent soil moisture and rainfall intensity (Schulze and Pike, 2008). The critical stormflow generating depth responsible for runoff is typically set to the depth of the A-horizon. The quick flow response fraction determines the percentage of stormflow or groundwater that becomes baseflow on any particular day.

3.4.2 Configuration of the ACRU model

The model was set up using the catchment characteristics given in Table 3.4. Initially the model was run using daily catchment rainfall, and later with the extended rainfall records. For each catchment in the study area daily rainfall data starting from 1949 up to 1994 was available from the raingauges in the catchment. The daily rainfall data was patched and extended as described in the previous section for it to be suitable for use in the model to simulate streamflow. Daily maximum and minimum temperature records from the South African Weather Service (SAWS) station and the Mike's Pass meteorological station were used. The daily A-pan equivalent potential evaporation values were derived using the Hargreaves and Samani (1985) equation which requires only daily maximum and minimum temperatures, as no daily measured evaporation records were available. Streamflow data from the gauging weirs at the outlet of each catchment were used.

The required soils inputs (Table 3.5) were obtained from Schulze *et al.* (2008). The catchment vegetation was natural grassland, *Themeda triandra,* for Catchments IV and VI.

Catchment IX was fire protected throughout the historical period and modelled as woodland. Appropriate land use changes to represent the commercial afforestation and subsequent planting to *Erogrostis curvula* were applied to Catchment III and VI to accurately simulate the historical streamflow. Monthly input parameter values for the vegetation variables used in the model are given in Table 3.6. The critical stormflow generating depth responsible for runoff was set to the depth of the A-horizon and the quick flow response fraction was set to 0.3 assuming that on any particular day 30% of the stormflow or groundwater becomes baseflow.

Table 3.4: Catchment attributes used as input in the ACRU model

Catchment	**Area (km^2)**	**Altitude (m.a.s.l)**	**MAP(mm)**	**Longitude**	**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° 14' 37.68" E	28° 59' 16.08" S	2508
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

Table 3.5: Soil characteristics of the A and B horizon used as input in the ACRU model

A Horizon						
Catchment	**Texture**	**Depth (m)**	**Wilting Point (WP) (m/m)**	**Field Capacity (FC)(m/m)**	**Porosity (PO)**	**A - B response (ABRESP)**
III	Loamy sand	0.3	0.134	0.225	0.438	0.38
VI	Silty loam	0.3	0.134	0.225	0.438	0.38
VI	Loamy sand	0.3	1.31	0.222	0.439	0.40
VII	Loam	0.30	0.130	0.221	0.439	0.41
IX	Silty loam	0.3	0.134	0.225	0.438	0.38
	B Horizon					
III	Loamy sand	0.53	0.155	0.247	0.410	0.38
VI	Silty loam	0.53	0.155	0.247	0.410	0.38
VI	Loamy sand	0.57	0.158	0.250	0.411	0.40
VII	Loam	0.56	0.162	0.252	0.410	0.41
IX	Silty loam	0.53	0.155	0.247	0.410	0.38

Table 3.6: Monthly values of water use coefficients, canopy interception per rainday, root mass distribution in the topsoil and coefficient of initial abstractions for the land uses occurring in the Cathedral Peak catchments (Schulze, 2004)

Landuse	**Variable**	**Months**											
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Natural grassland	CAY	0.7	0.7	0.7	0.5	0.3	0.2	0.2	0.2	0.5	0.65	0.7	0.7
	VEGINT	1.6	1.6	1.6	1.4	1.2	1	1	1	1.3	1.6	1.6	1.6
	ROOTA	0.9	0.9	0.9	0.95	1	1	1	1	0.95	0.9	0.9	0.9
	COIAM	0.15	0.15	0.25	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.15
Pinuspatula	CAY	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	VEGINT	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	ROOTA	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	COIAM	0.15	0.15	0.25	0.3	0.3	0.3	0.3	0.3	0.2	0.23	0.2	0.15
Erogrostiscurvula	CAY	0.43	0.44	0.4	0.32	0.2	0.2	0.2	0.2	0.25	0.3	0.37	0.42
	VEGINT	1.1	1.2	1.2	1	0.85	0.85	0.85	0.85	0.7	0.78	0.9	0.95
	ROOTA	0.9	0.9	0.9	0.95	1	1	1	1	1	0.95	0.9	0.9
	COIAM	0.15	0.15	0.25	0.3	0.3	0.3	0.3	0.3	0.2	0.23	0.2	0.15

3.4.3 Verification of the ACRU model

Initially the model was set up using the catchment rainfall. The historical streamflow data used for the verification was for the period 01/01/1973 – 31/12/1981. The performance statistics (Table 3.7) show relatively high R^2 values for the simulations using the catchment rainfall with a slope close to 1 and intercept of close to 0 which indicated an adequate simulation of streamflow.

Once the model configuration had been validated for the catchments the ACRU model was rerun using the rainfall records extended using the Cathedral Peak Hotel rainfall. This was done to allow for a longer simulation period as the Cathedral Peak Hotel rainfall had been recorded since 1882 to present day. The performance statistics in Table 3.8 showed a poorer simulation using the extended rainfall when compared to the simulation using the catchment rainfall.

Although poor simulation results were obtained when using the rainfall records extended using the Cathedral Peak Hotel rainfall further investigation of the simulated and observed streamflow demonstrated the satisfactory model performance in the simulation of streamflow (Figures 3.3 to 3.5). The simulation for Catchments IV and VII (Figure 3.3 and 3.4) displayed a strong relationship between the simulated and observed streamflow, thus indicating a good simulation of both high and low flows, which is evident in the relatively high $R^2$and Coefficient of Agreement values for both catchments. The average error in flow and standard deviation of the simulated streamflow both met the requirements and fell within the 10 mm/day threshold. Catchment IX (Figure 3.5) shows that the high flows were well simulated while the low flows were slightly under simulated even though there was an under simulation of the low flows the average error in flows and standard deviation fell within the required threshold. From this simulation the stormflow is not responsive because the Coefficient of Initial Abstraction values may have been too high causing a delay in the stormflow generation resulting in the under simulation of low flows. However, despite this shortfall the good simulation of high flows was satisfactory, and thus the simulation was considered acceptable.

Table 3.7: Statistics of performance of the ACRU model for the Cathedral Peak Catchments: Comparison of daily observed and simulated values using the catchment rainfall (1973 - 1981)

	III	IV	VI	VII	IX
Total observed flows (mm)	4456	7225	7537	5828	5816
Total simulated flows (mm)	7919	5001	4679	4962	5077
Ave. Error in flow (mm/day)	1.053	-0.761	-0.978	-0.297	-0.225
Mean observed flows	1.356	2.473	2.58	1.995	1.769
Mean simulated flows	2.409	1.712	1.601	1.698	1.545
Std. Deviation of observed flows	2.037	3.208	2.688	2.518	1.872
Std. Deviation of simulated flows	3.122	2.41	2.345	2.393	2.145
Coefficient of Agreement	0.907	0.893	0.957	0.984	0.954
Correlation Coefficient: Pearson's (r)	0.841	0.945	0.921	0.968	0.915
Regression Coefficient (slope)	1.288	0.71	0.803	0.92	1.048
Regression Intercept	0.663	-0.043	-0.417	-0.137	-0.31
Coefficient of Determination: R^2	0.706	0.893	0.848	0.938	0.837

Table 3.8: Statistics of performance of the ACRU model for the Cathedral Peak Catchments: Comparison of daily observed and simulated values using the extended rainfall records (1973 -1981)

	III	IV	VI	VII	IX
Total observed flows (mm)	21882	27763	24387	17499	19747
Total simulated flows (mm)	26293	19884	13219	17777	11690
Ave. Error in flow (mm/day)	0.314	-0.553	-0.862	0.022	-0.653
Mean observed flows	1.556	1.949	1.883	1.398	1.601
Mean simulated flows	1.87	1.396	1.021	1.42	0.998
Std. Deviation of observed flows	2.132	2.39	2.191	2.303	1.645
Std. Deviation of simulated flows	2.533	1.98	1.704	2.056	1.56
Coefficient of Agreement	0.872	0.921	0.748	0.827	0.896
Correlation Coefficient: Pearson's (r)	0.788	0.862	0.64	0.733	0.825
Regression Coefficient (slope)	0.936	0.714	0.498	0.654	0.782
Regression Intercept	0.414	0.004	0.084	0.506	-0.305
Coefficient of Determination: R^2	0.621	0.743	0.409	0.537	0.68

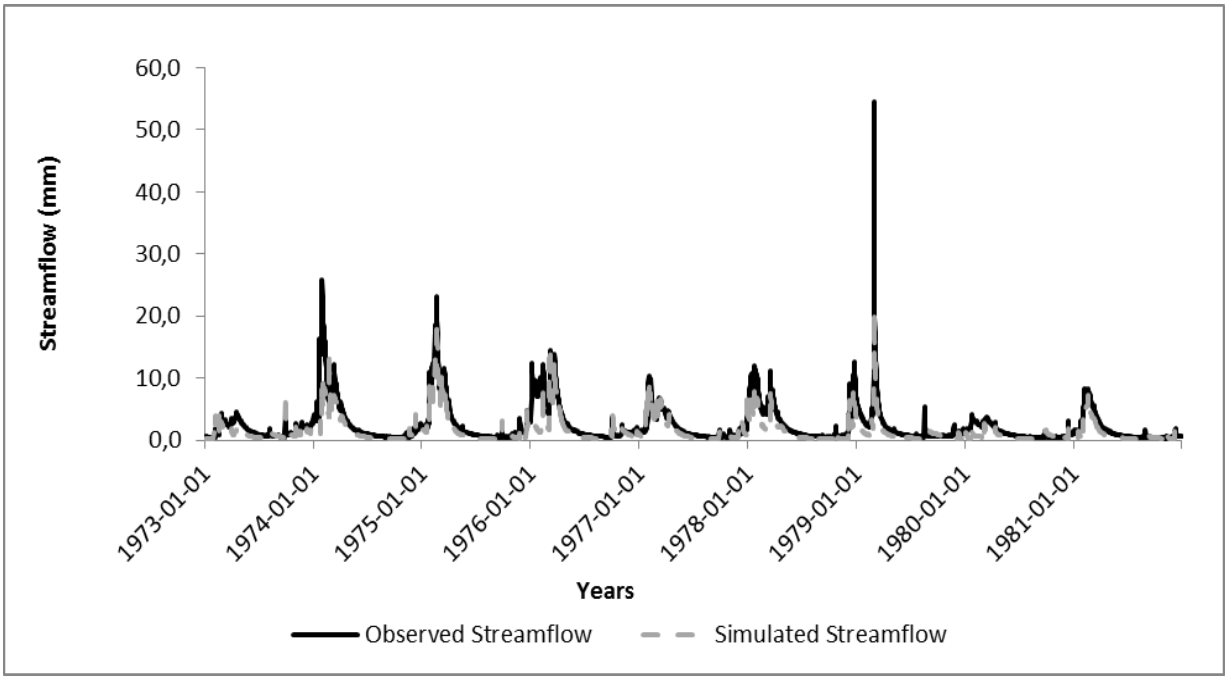

Figure 3.3: Time series of observed and simulated streamflow for Catchment IV

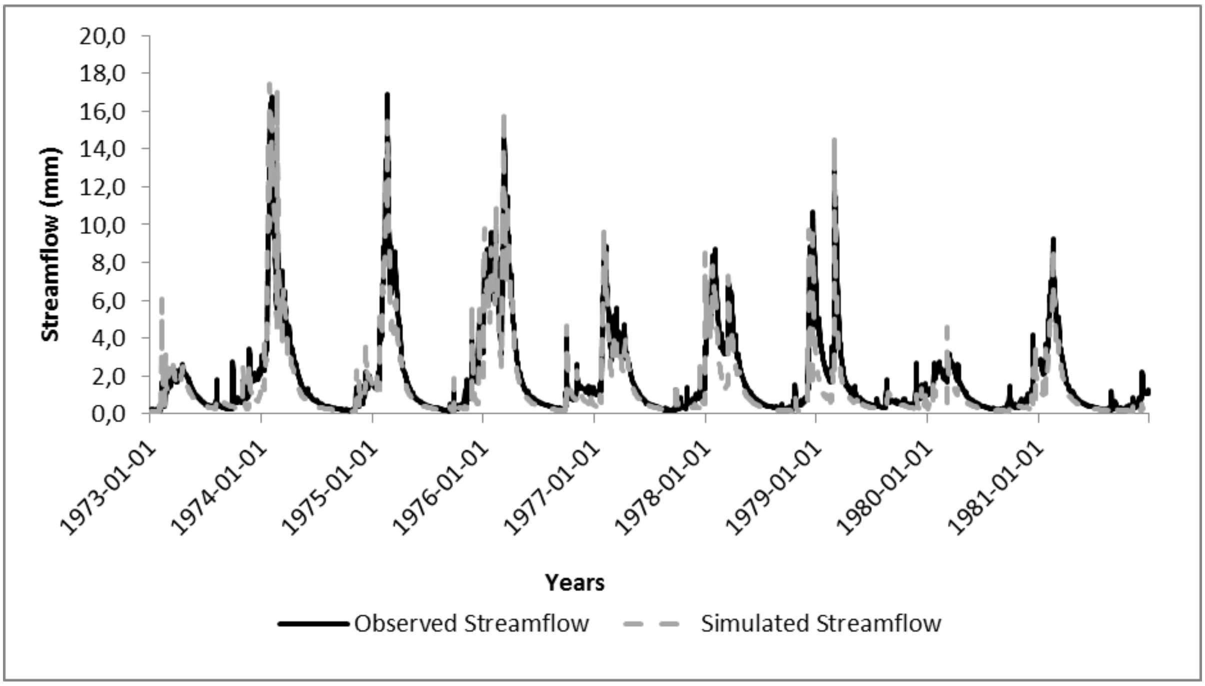

Figure 3.4: Time series of observed and simulated streamflow for Catchment VII

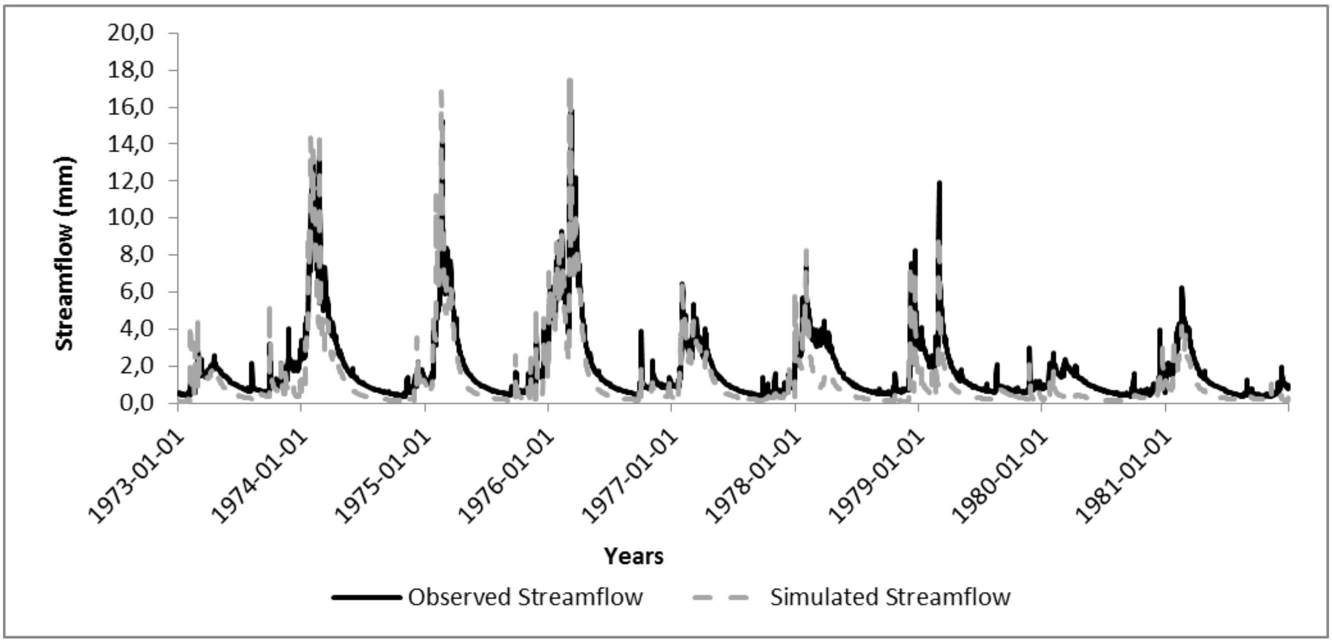

Figure 3.5: Time series of observed and simulated streamflow for Catchment IX

3.5 Statistical Tests and Methods 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 (Kundzewicz and Robson, 2000; Gocic and Trajkovic, 2013; Sayemuzzaman and Jha, 2014). Parametric tests are usually based on linear models and normal theory. 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 the data records (Tesemma, 2009). The following section reviews and describes the statistical tests and methods that will be used in this study to detect monotonic trends in climatic and hydrological data.

3.5.1 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 by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} a_{ij} \tag{3.2}$$

Where

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

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, 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; Jhajharia *et al.*, 2013; Sayemuzzaman and Jha, 2014). 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, which is calculated from the sign of differences and not from the value of the variable thus minimising the influence of outliers (Önöz and Bayazit, 2003). Greater power is achieved for skewed distributions and data below the detection limit which 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; Duhan and Pandey, 2013; Gocic and Trajkovic, 2013; Kalumba *et al.*, 2013).

The Mann-Kendall test 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 Mann-Kendall test (Hirsch *et al*., 1982) accounts for seasonality by computing the Mann-Kendall test on each of the 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 are 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). Yue and Wang (2002); Hamed (2008); Duhan and Pandey (2013) and Sayemuzzaman and Jha (2014) 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 that was proposed by Hamed and Rao (1998). 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).

Duhan and Pandey, (2013), Sonali and Kumar (2013), and Sayemuzzaman and Jha (2014), 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, which 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, Yue and Wang (2002) and Duhan and Pandey (2013) suggest that there is no need for the modified Mann-Kendall test as there is 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.

The value of the Mann-Kendall test as a powerful statistical test is evident from the literature reviewed hence it is commonly used in detecting trends. Yue and Wang (2002), Caloiero *et al*. (2011), Duhan and Pandey (2013) and Sayemuzzaman and Jha (2014) have used the Mann-Kendall test to detect trends in rainfall in India, Italy and the United States. Streamflow trends across the world have been investigated by Molnar and Ramirez (2001), Abdul Aziz and Burn (2006), Gautam *et al*. (2010), Li *et al*. (2011), Abghari *et al*. (2013) and Kornmann *et al*. (2014). Temperature studies have been conducted using Mann-Kendall in India by Jhajharia *et al*. (2013) and Sonali and Kumar (2013) as well as Mohsin and Gough (2006) in Toronto, Canada.

3.5.2 Sen’s Slope Estimator

The Mann-Kendall statistical test is often used in combination with the Sen’s slope estimator. 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 (Shahid, 2011; Gocic and Trajkovic, 2013; Sayenmuzzaman and Jha, 2014). The Sen’s slope estimator or Theil-Sen approach 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; Gocic and Trajkovic, 2013; Sayenmuzzaman and Jha, 2014). The Sen's slope estimator is denoted as (Shahid, 2011):

$$Q' = \frac{x_{t'} - x_t}{t' - t} \tag{3.3}$$

Where

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. Shahid, 2011; Abghari *et al*., 2013; Jhajharia *et al*., 2013; Sonali and Kumar, 2013; Sayemuzzaman 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 has been documented in the literature. With both statistical methods regarded as well complementary thus demonstrating their value as applicable statistical tests to be used to test for significance as well as the magnitude of trends.

3.5.3 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 is Wilcoxon-Mann-Whitney (Nachar, 2008; Mustapha, 2013). 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 Nachar (2008) and Mustapha (2013) the Mann-Whitney test is one of the most powerful non-parametric tests for testing the difference between populations. Furthermore, 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:

$$U = n1n2 + \frac{n2(n2+1)}{2} - R1 \tag{3.4}$$

Where

U = Mann-Whitney statistic

n1= Sample size of group one

n2= sample size of group two

R1 = Rank of the sample size

3.5.4 Indicators of Hydrological Alteration

To enhance the results of the streamflow analysis the Indicators of Hydrological Alteration software (IHA) was also used to check for statistically significant historical trends and differences between the historical and current data. The IHA software is a suite of statistics originally developed by Richter *et al*. (1998) of the US Nature Conservancy to characterise natural flow conditions and evaluate the extent of human-induced changes to natural flow regimes (Mathews and Richter, 2007; Gao *et al*., 2009). The program was designed to calculate statistics based on their hydrological and ecological relevance as well as their ability to provide information on the temporal changes in flow regimes using dam operation, water diversions, ground water pumping and landscape or catchment modification as indication of change.

The IHA program uses a suite of 67 parameters subdivided into two groups. The first group is a set of 33 IHA parameters while the second group consists of 34 Environmental Flow Component (EFC) parameters. Together they are used to characterise the intra- and inter-annual flow variability using five flow characteristics broadly categorised into magnitude, duration, timing, frequency and rate of change of flow (Mathews and Richter, 2007; Gao *et al*., 2009). The IHA software is valued for its ease of operation, its ability to capture and reflect the full range of hydrological variation using a small range of statistics, its rapid processing and tabular summaries and graphical outputs (Mathews and Richter, 2007; Gao *et al*., 2009). Given these characteristics, the IHA is commonly used to assess the difference in flow regimes between past (pre-impact) and present (post-impact) time periods (Gao *et al*., 2009). The parameters chosen for use in this study are provided in Table 3.9.

Table 3.9: Summary of the Indicators of Hydrologic Alteration parameters used in the study (modified from Richter *et al*. 1998)

IHA statistics group	**Regime characteristics**	**Hydrologic attributes**
Group 1: Magnitude of monthly water conditions	Magnitude Timing	Median for each calendar month (January – December)
Group 2: Magnitude and duration of annual extreme water condition	Magnitude Duration	Annual minimums of 1-day means Annual maximums of 1-day means Annual minimums of 3-day means Annual maximums of 3-day means Annual minimums of 7-day means Annual maximums of 7-day means Annual minimums of 30-day means Annual maximums of 30-day means Annual minimums of 90-day means Annual maximums of 90-day means

3.6 Summary of Methodology to be Followed

Two periods of rainfall, temperature and streamflow data were available for the trend detection study, a historical data period which varied in length and a short current data period. Following the review of 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 period between 1948 and 1994. 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 the data was separated into 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 data 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 (1948 - 1994) and current data (2012 - present). The events chosen varied depending on the hydroclimatic variable. The IHA software was chosen to facilitate the streamflow analysis of the Cathedral Peak catchments because it is a useful tool in assessing change in the hydrologic regime and can provide information on understanding human induced impacts (Richter *et al*., 1998). The combination of the statistical analysis and the IHA software was viewed to be more robust in finding significant changes in the climatic and hydrological data. The results from the detection study are presented in the sections which follow.

4. RESULTS OF THE TREND DETECTION ANALYSIS UNDERTAKEN FOR THE CATHEDRAL PEAK REGION

The results of the trend detection study for both the historical period and the comparison of the historical and current records undertaken for the Cathedral Peak region are presented in this chapter starting with the trends in temperature, followed by the trends in rainfall and lastly the streamflow trends.

4.1 Trends in the Temperature of the Cathedral Peak Region

The trend detection was carried out using two analyses. The first analysis used the Mann-Kendall test together with Sen's slope estimator to detect trends in the historical records of the research area. The second analysis used the Mann-Whitney test to detect significant differences between the historical (1948 – 2000) and current (2012 – 2015) 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.

4.1.1 Trends in the historical temperature records between 1955 and 2000

Historical temperature records were available from Office meteorological station located near the entrance to the Cathedral Peak reserve at a lower altitude for the period 1972 to 1993, from the Mike's Pass meteorological station at a higher altitude for the period 1955 to 1984 and the Cathedral Peak Forest station (0299417A) for the period 1970 to 2000. The Mann-Kendall test and Sen's Slope estimator were used to detect historical trends in temperature. To determine significant differences between the current and historical temperature datasets the Mann-Whitney test was used.

Statistically significant positive trends were detected in the daily maximum and daily average temperatures for all three stations (Table 4.1), with the Office meteorological station and the Cathedral Peak Forest station also showing statistically positive trends in the daily minimum temperatures (Table 4.1). This 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 3.942^{o}C, 0.728^{o}C, 4.233^{o}C and 4.32^{o}C, respectively, for the Office meteorological station from 1955 to 2000. At Mike's Pass meteorological station the daily maximum and daily average temperatures have increased by 1.84^{o}C and 1.20^{o}C. The daily maximum, minimum and mean temperatures have increased by 1.558^{o}C, 0.168^{o}C, 1.494^{o}C and the monthly and annual minimum temperatures have increased by 2.7^{o}C and 5.4^{o}C at the Cathedral Peak Forest from 1970 to 2000 (Table 4.1).

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 indicative of warming was detected at the Cathedral Peak Forest station (Table 4.1).

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 occurrence of trends in each of the seasons.

For the Office meteorological station (Table 4.1) statistically significant positive trends were detected for the summer minimum, autumn maximum, and winter maximum and minimum temperatures. Results indicated that the specified temperatures have increased by 0.045^{o}C, 0.045^{o}C, 0.039^{o}C, and 0.018^{o}C, respectively, from 1955 to 2000. Statistically positive trends were found for the Mike's Pass meteorological station for summer maximum and minimum temperatures with an increase of 0.022^{o}C and 0.007^{o}C respectively. A statistically significant negative trend was evident in the winter minimum temperatures with a temperature decline of 0.007^{o}C from 1955 to 2000. Analysis of the Cathedral Peak Forest station records showed statistically significant positive trends in the summer minimum and winter and spring maximum and minimum temperatures. The Sen's slope estimator indicated that the summer minimum temperatures have increased by 0.015^{o}C, winter maximum and minimum

Table 4.1: Results of the Mann-Kendall test and Sen’s slope estimator applied to the temperature records from the Cathedral Peak area

	Office Met Station Temperature Trends				Mike’s Pass Temperature Trends				Cathedral Peak Forest			
	MK Test (S)	**P value**	**Sen's Slope per time step**	**Trend**	**MK Test (S)**	**P value**	**Sen's Slope per time step**	**Trend**	**MK Test (S)**	**P value**	**Sen's Slope per time step**	**Trend**
Daily Max	1089865,0	<0,0001	0,0002406	Trend (+)	981009,0	0,007	0,0001119	Trend (+)	1187785	0,003	0,00009487	Trend (+)
Daily Min	501076,0	0,011	0,0000443	Trend (+)	545147,0	0,138	0,00005798	No Trend	2463084	<0.0001	0,00001025	Trend (+)
Daily Mean	1591379,0	<0,0001	0,0002577	Trend (+)	768257,0	0,037	0,00007349	Trend (+)	1938844	<0.0001	0,00009102	Trend (+)
Monthly Max	3302,0	0,010	0,008	Trend (+)	562,0	0,798	0,00003067	No Trend	3012	0,209	0,002	No Trend
Monthly Min	782,0	0,545	0,002	No Trend	1031,0	0,639	0,0009302	No Trend	5361	0,025	0,005	Trend (+)
Annual Max	28,0	0,381	0,062	No Trend	-5,0	0,943	0	No Trend	45	0,454	0,025	No Trend
Annual Min	13,0	0,697	0,04	No Trend	4,0	0,957	0	No Trend	199	0,001	0,123	Trend (+)
Frost Events	-76512	0.073	0	No Trend	75888	0,351	0	No Trend	-380404	<0.0001	0	Trend (-)

Seasonal Temperature Trends

	Office Met 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**
Summer Max	-7757,0	0,013	-0,001	No Trend	209549,0	<0.0001	0,0004854	Trend (+)	45650	0,377	0,0001237	No Trend
Summer Min	44468,0	<0.0001	0,001	Trend (+)	126919,0	0,009	0,0001612	Trend (+)	377037	<0,0001	0,0003435	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	0,112	0,000244	No Trend	72207,0	0,124	0,0001215	No Trend	62165	0,221	0,00008951	No Trend
Winter Max	32000,0	0,014	0,0008734	Trend (+)	41626,0	0,364	0,00008917	No Trend	202590	<0,0001	0,0003517	Trend (+)
Winter Min	76526,0	0,002	0,0004071	Trend (+)	-97853,0	0,033	-0,000163	Trend (-)	352690	<0,0001	0,0004484	Trend (+)
Spring Max	27306,0	0,235	0,0003096	No Trend	11809,0	0,793	0	No Trend	99109	0,047	0,0003183	Trend (+)
Spring Min	25743	0,28	0,0001326	No Trend	-58948	0,192	-0,0001282	No Trend	301221	<0,0001	0,0004376	Trend (+)

temperatures have increased by 0.016^{o}C and 0.02^{o}C and the maximum and minimum temperatures for spring have increased by 0.014^{o}C and 0.02^{o}C from 1955 to 2000 (Table 4.1).

Temperature changes have been the focus of recent mountain climate research due to the sensitive and highly dynamic nature of the microclimate. The rapid changes in climate can provide early detection signals as it has been observed that slight temperature changes in lowlands are often amplified in mountainous regions (Rangwala and Miller, 2010). Although the significant seasonal trends detected between 1955 and 2000 translate to less than 1^{o}C of change, the rising daily, monthly and annual temperatures (showing increases of up to 4^{o}C and more) are an indication of the global warming impacts regarded as drastic changes for mountainous climates.

4.1.2 Comparative analysis between the historical and current temperature records

A comparative analysis which tested 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 the Mann-Whitney test was undertaken. No records beyond the year 2000 were available for the Cathedral Peak Forest station thus it could not be included in this analysis. The Mann-Whitney test 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_o, a difference in the median or central value 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 difference, is rejected.

No difference in the number of days where the maximum temperature is greater than 30^{o}C was evident for summer for the Mike's Pass meteorological station (Table 4.2). 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 meteorological station the results showed that there was no significant difference in the number of days where the maximum temperature is greater than 30^{o}C in summer while, significant decreases were 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, while the results from summer, autumn and spring were inconclusive. 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 (Table 4.2).

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. A significant increase in the number of days where the minimum temperature is less than 5^{o}C was detected for winter. There was no significant difference in the number of days where the minimum temperature is less than 5^{o}C for autumn, winter and spring at the Office station while the results for summer were inconclusive. 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 4.2).

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 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.

Table 4.2: Results of the Mann-Whitney test for the comparative analysis of threshold events per season for the Top Met 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	None	400,5	<0,0001	Sign.(+)	405	<0,0001	Sign.(-)	370	<0,0001	Sign.(-)
Greater than 35°C	400,5	<0,0001	Inconcl.	396	<0,0001	Inconcl.	450	<0,0001	Sign.(+)	478,5	<0,0001	Inconcl.
Less than 5°C	445,5	0,726	None	465,5	0,374	None	711	0,001	Sign.(+)	478,5	0,642	None
Frost events	400,5	<0,0001	Inconcl.	432	0,0903	None	563	0,123	None	572	0,216	None
Monthly Mean	225	0,03	Sign. (-)	285	0,172	None	151	0	Sign.(-)	420	0,28	None

	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	None	71	<0.0001	Sign.(-)	63.5	<0.0001	Sign.(-)	86.5	<0.002	Sign.(-)
Greater than 35°C	161	<0.0001	Sign.(-)	90	<0.0001	Inconcl.	90	<0.0001	Inconcl.	186	<0.0001	Sign.(-)
Less than 5°C	189	<0.0001	Inconcl.	115	0.484	None	122.5	0.34	None	285.5	0.431	None
Frost events	189	<0.0001	Inconcl.	94.5	0.277	None	115	0.463	None	256	0.626	None
Monthly Mean	98	0.052	None	92	1	None	86	0.915	None	190	0.386	None

4.2 Trends in the Rainfall of the Cathedral Peak Region

The rainfall analysis was carried out in two steps. The first analysis used the Mann-Kendall test together with Sen's slope estimator to detect trends in the historical daily, monthly, seasonal and annual records of the raingauges in the research area. The second analysis used the Mann-Whitney test to detect significant differences between the historical (1948 – 1993) and current (2012 – 2015) 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.

4.2.1 Trends in the historical rainfall records between 1948 and 1993

Trends at a daily, monthly, seasonal and annual time scale were considered. Daily rainfall records were only available for seven raingauges, five stations were located in the catchments and the remaining at 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 4.3; Figure 4.1).

Table 4.3: 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	0,353	0,000085	No Trend
IVA	-5247167,0	< 0.0001	0,000000	Trend (-)
VIB	-2675283,0	< 0.0001	0,000046	Trend (-)
VIIA	-9576092,0	< 0.0001	0,000046	Trend (-)
IXA	1850648,0	< 0.0001	0,000145	Trend (+)
Mike's Pass	-199366,0	0,654	0,000104	No Trend
Office Met	-604440,0	0,001	0,000127	Trend (-)

Raingauges IVA, VIB, VIIA and the Office meteorological station had significant negative trends, with a decline of 0 mm, 0.8 mm and 2.3 mm from 1948 to1993. These raingauges are located in the interior of the catchment, quite close to each other, except for Office meteorological station (Figure 4.1). Gauge IXA, located on the eastern side of the research area (Figure 4.1), showed a positive trend indicating increase of 2.6 mm over the period of record (Table 4.3). No significant trends were detected for gauge IIIA and Mike’s Pass meteorological station (Table 4.3).

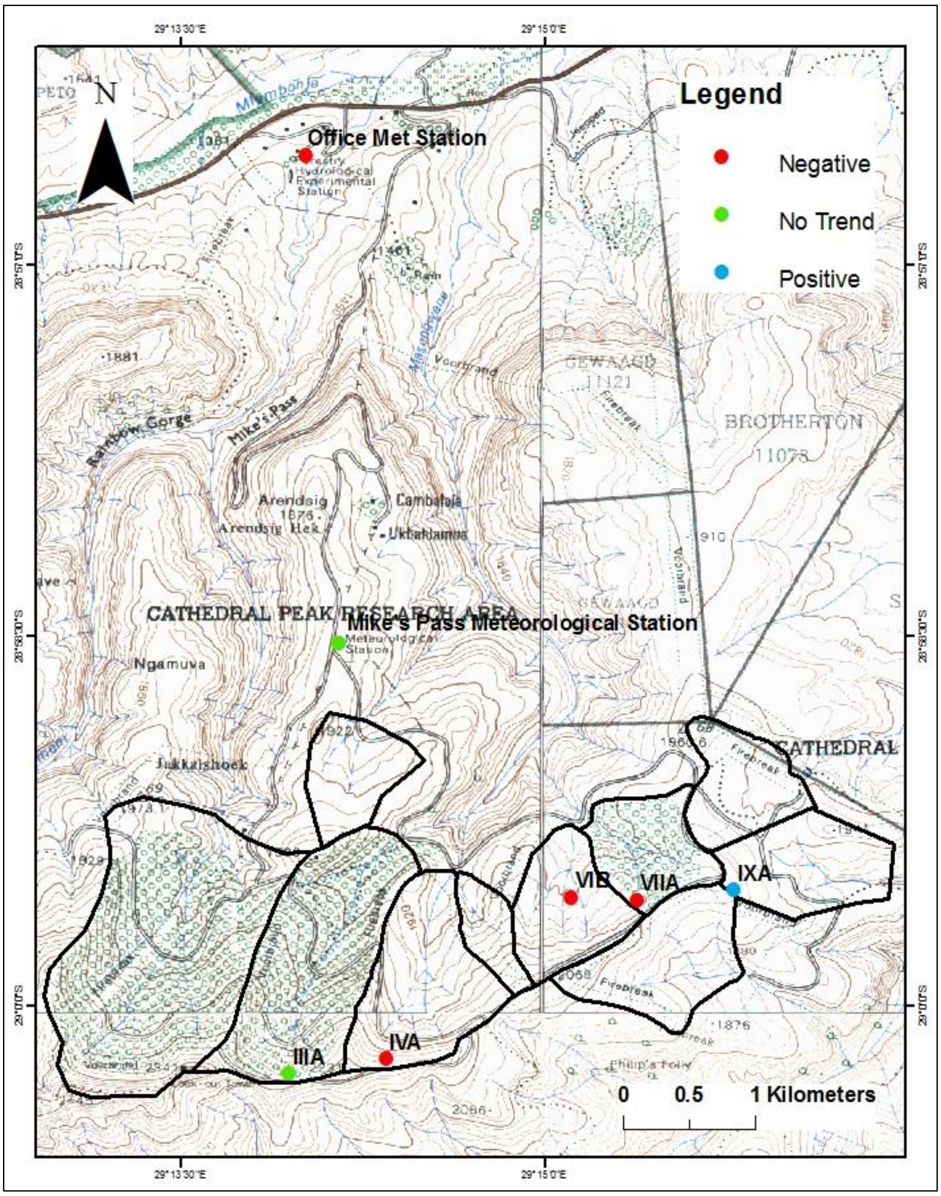

Figure 4.1: Spatial location of daily raingauges and associated trends between 1949 and 1993

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. Twelve of the 23 raingauges showed statistically significant monthly trends (Table 4.4). Raingauges IA, IIA, IIIA, IIIB, IVA, IVC, VA, VIIA, VIIB, VIIIC and

IXC showed statistically significant negative trends. The negative monthly trends shown for gauge IVA and VIIA were consistent with the negative rainfall trends at a daily time step. A statistically significant positive trend was shown for 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, for Catchment X, which lies on the leeward slope, rainfall may result from a frontal system. No trends were found in the annual data (Table 4.4). The Sen's Slope estimate for raingauges with significant trends varied between 67.0 mm and 100 mm over the period 1948 – 1993 (Table 4.4).

Table 4.4: 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	0,024	-0,139	Trend (-)	-52	0,098	-24,179	No Trend
IIA	-2881,0	0,021	-0,170	Trend (-)	-46	0,146	-21,758	No Trend
IIB	-1784,0	0,154	-0,104	No Trend	-48	0,128	-21,953	No Trend
IIC	-1313,0	0,294	-0,065	No Trend	-38	0,233	-12,224	No Trend
IIIA	-2485,0	0,047	-0,130	Trend (-)	-42	0,186	-20,025	No Trend
IIIB	-2646,0	0,034	-0,136	Trend (-)	-48	0,128	-24,24	No Trend
IVA	-2984,0	0,017	-0,158	Trend (-)	-54	0,086	-27,681	No Trend
IVC	-2850,0	0,023	-0,133	Trend (-)	-46	0,146	-19,611	No Trend
VA	-2695,0	0,031	-0,132	Trend (-)	-48	0,128	-21,747	No Trend
VIB	-2443,0	0,051	-0,121	No Trend	-60	0,055	-22,441	No Trend
VIIA	-2700,0	0,031	-0,121	Trend (-)	-40	0,209	-19,234	No Trend
VIIB	-2566,0	0,040	-0,131	Trend (-)	-58	0,064	-22,194	No Trend
VIIC	-1559,0	0,213	-0,068	No Trend	-54	0,086	-18,981	No Trend
VIIIA	-1125,0	0,369	-0,047	No Trend	-46	0,146	-10,148	No Trend
VIIIC	-2865,0	0,022	-0,137	Trend (-)	-54	0,086	-22,458	No Trend
IXA	-2360,0	0,059	-0,104	No Trend	38	0,233	-14,78	No Trend
IXB	-1116,0	0,373	-0,041	No Trend	32	0,319	-10,339	No Trend
IXC	-2835,0	0,023	-0,114	Trend (-)	44	0,165	-17,876	No Trend
XA	2926,0	0,019	-0,135	Trend (+)	-52	0,098	-21,496	No Trend
XB	2329,0	0,063	-0,101	No Trend	-46	0,146	-17,705	No Trend
XC	1654,0	0,186	-0,067	No Trend	-50	0,113	-14,952	No Trend
Mike's Pass	-971,0	0,438	-0,046	No Trend	-22	0,501	-5,242	No Trend
Office Met	-683,0	0.597	-0.015	No Trend	-46	0.146	-15.652	No Trend

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 which is evident in the higher magnitude of change observed at the daily and monthly time scale when compared to the annual results. A 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 Rao, 1998 and Yue and Wang, 2002). Therefore, 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 was applied to test for the occurrence of trends in each of the seasons. The premise for this test was set that the null hypothesis (H_o) stated that there was a seasonal trend in the times series and the alternative hypothesis (H_a) stated that there was no seasonal trend in the times series.

No statistically significant trends were detected for summer and winter (Table 4.5). Significant negative trends were detected for autumn for five raingauages IA, IVC, VIB, VIIB and VIIIC indicating a decrease in autumn rainfall of 44.3 mm, 43.5 mm, 43.1 mm, 48.7 mm and 48.2 mm respectively from 1948 to 1993. The only statistically significant trend for spring was a negative trend for gauge IIA indicating a decline of 63.8 mm in rainfall from1948 to1993, statistically insignificant trends were detected for the remainder of the raingauges (Table 4.5).

At a seasonal time scale, the results indicated that besides a decline in autumn rainfall, no trends were evident in the seasonal rainfall for the historical period. According to IPCC reports, evidence of climate change has become greater and more pronounced in recent studies. Authors such as Mazvimavi (2010) agree and are of the belief that changes prior to 2000 are far less than those observed post 2000. The above results concur with these reports as changes in rainfall were not statistically significant in the historical records. Given, the lack of significant results, a comparative study using the historical (1948 - 1993) and current (2012 - 2015) rainfall data was undertaken to determine if any significant differences between the two groups of data were evident.

Table 4.5: 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)**			
	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**
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
Off Met	69	0.687	0.267	No Trend	-293	0.069	-0.815	No Trend	59	0.711	0.005	No Trend	-5	0.981	-0.029	No Trend

4.2.2 Comparative analysis of the historical and current rainfall records

The comparative analysis made use of the relatively long historical daily record and the short current daily record obtained from the re-established raingauges (approximately two years of data). A majority of the historical raingauges recorded data at a monthly time step hence, the comparative analysis was conducted for the raingauges that had daily data for both current and historical periods. Due to the short record length and to eliminate any bias the smallest scale at which both records could be analysed was used, thus much of the comparative analysis was performed at a seasonal scale. 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 two consecutive days) and lastly threshold events which analysed the number of days when the rainfall exceeded 20 mm and 30 mm per day per season. A rainday in the Drakensberg region is defined as one on which more than 0.5 mm 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 only six raingauges was used because there were only six daily raingauges recording during the historical period.

The results showed that, for summer, the number of raindays have increased significantly between the historical and current period for the records from raingauge IVA and the Mike's Pass meteorological station, while no differences were evident for the remainder of the raingauges (Table 4.6). Raingauge IVA showed a similar increase in the number of raindays in autumn and winter (Table 4.6), correlated to this was the significant decrease in the number of dry days found 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 4.6). 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. A significant decrease in the number of dry days for raingauge IVA was evident for winter (Table 4.6). Thresholds events exceeding 20 mm 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 4.6). For rainfall events exceeding 30 mm, 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 4.6).

Table 4.6: Results of the Mann-Whitney test for the comparative analysis of the number of raindays, number of dry days and threshold events per season

	No. of raindays											
	Summer			**Autumn**			**Winter**			**Spring**		
	U	**P value**	**Difference**	**U**	**P value**	**Difference**	**U**	**P value**	**Difference**	**U**	**P value**	**Difference**
IIIA	83	0.983	None	115	0.359	None	155.5	0.017	Sign.(+)	68.5	0.657	None
IVA	162.5	0.003	Sign. (+)	161	0.005	Sign.(+)	162	0.005	Sign.(+)	85.5	0.918	None
VIB	141	0.107	None	110	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	Sign.(+)	65	0.537	None
Mike’s Pass	163	0.002	Sign. (+)	110	0.474	None	113	0.369	None	62	0.497	None
	No. of dry days											
	Summer			**Autumn**			**Winter**			**Spring**		
	U	**P value**	**Difference**	**U**	**P value**	**Difference**	**U**	**P value**	**Difference**	**U**	**P value**	**Difference**
IIIA	138	0.112	None	65	0.574	None	16.5	0.012	None	106.5	0.505	None
IVA	93	0.991	None	117	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**	**Difference**	**U**	**P value**	**Difference**	**U**	**P value**	**Difference**	**U**	**P value**	**Difference**
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**	**Difference**	**U**	**P value**	**Difference**	**U**	**P value**	**Difference**	**U**	**P value**	**Difference**
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

The analysis of the daily maximum rainfall showed a significant decrease in rainfall between the historical and current periods for raingauge IXA, while no differences were evident for the remaining raingauges (Table 4.7). Raingauges IIIA, IVA and VIB showed significant increases in 2-day maximum rainfall between the historical and current period (Table 4.7). The monthly maximum rainfalls for raingauges IIIA, IVA, VIB and VIIB were found to have increased significantly between the historical and current period (Table 4.8).

Table 4.7: Results of the Mann-Whitney test for the comparative analysis of total daily rainfall and 2-Day maximum

	Daily Total			**2-Day Maximum Rainfall**		
	U	**P value**	**Difference**	**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

Table 4.8: Results of the Mann-Whitney test for the comparative analysis of the total monthly rainfall

	U	**P value**	**Difference**
IIA	3030	0.056	None
IIC	2455	0.822	None
IIIA	3251	0.031	Sign.(+)
IIIB	2567	0.914	None
IVA	3980	<0.0001	Sign.(+)
VA	2957	0.371	None
VIB	3337.5	0.045	Sign.(+)
VIIA	2967	0.342	None
VIIB	3827	<0.0001	Sign. (+)
VIIC	2966	0.357	None
VIIIA	2843.5	0.348	None
VIIIC	2984.5	0.173	None
IXA	2675.5	0.664	None
IXB	2581	0.881	None
IXC	2410	0.719	None
XA	2373.5	0.791	None
XC	2458.5	0.882	None
Mike’s Pass	2976	0.181	None

Trend detection studies are often subject to uncertainty because of lack of precise understanding due to limited data as a result of 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.

4.3 Trends in the Streamflow of the Cathedral Peak Region

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 groups of data.

4.3.1 Trends in the historical streamflow records between 1949 and 2000

Extended streamflow (as described in Section 3.4) 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, with the decline ranging between 0.484 mm and 1.303 mm and 15.3 and 41.616 mm respectively, from 1949 to 2000. Statistically significant negative trends in the annual streamflow data were detected for Catchments III, IV, VII and IX with the decrease ranging between 329.511 mm and 830.841mm over the record period, while no trends were found at Catchment VI (Table 4.9).

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 at all the gauging stations were shown with declines in streamflow over the period 1949 – 2000 ranging between 12.036 mm and 37.893 mm for summer, and 11.067 mm and 31.161 mm for autumn. In winter all catchments except Catchment VI showed a decline of between 2.958 mm and 7.854 mm. For spring significant negative trends were detected for Catchments III, IV, VII and IX, with declines ranging between 2.04 mm and 5.865 mm (Table 4.10).

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^3sec^{-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 4.11) are consistent with those obtained from the Mann-Kendall test and Sen's Slope estimator (Table 4.9 and 4.10).

The results show a combination of significant and insignificant negative trends for all the catchments. A significant decrease in the monthly flows was found at Catchment III and IV for the whole year excluding October. The decline in streamflow was between 0.00064 and 0.0011 m^3sec^{-1} per month for Catchment III and between 0.00009 and 0.00127 m^3sec^{-1} per month for Catchment IV. A significant decrease in the monthly flows was found at Catchment IX for the whole year excluding March and October with a decline ranging between 0.00003 and 0.0005 m^3sec^{-1} per month. A significant decline in the monthly flows was found for November and December for Catchment VI and from May to September for Catchment VII. The decline per month for Catchment VI and VII was between 0.00009 and 0.00019 m^3sec^{-1} and 0.00002 and 0.00009 $m^3sec\text{-}^{1}$ respectively. A significant decline in the maximum and minimum flows was detected for Catchments III, IV and IX ranging between 0.00002 and 0.002 m^3sec^{-1}, 0.01 and 0.00009 and 0.0025 and 0.00001 and 0.0004 m^3sec^{-1} respectively. While, no trends were detected for Catchments VI and VII with the exception of a significant decline in the 1-day minimum flow as well as the 90-day maximum and minimum flows found at Catchment VII. 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 4.11).

Table 4.9: 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	-28246612	<0.0001	-0,00002899	Trend (-)	-31682	<0.0001	-0,031	Trend (-)	-342	<0.0001	-10,114	Trend (-)
IV	-68700684	<0.0001	-0,00007042	Trend (-)	-74024	<0.0001	-0,068	Trend (-)	-598	<0.0001	-16,291	Trend (-)
VI	-21364737	<0.0001	-0,0000418	Trend (-)	-23586	<0.0001	-0,04	Trend (-)	-198	0,054	-5,681	No Trend
VII	-25919196	<0.0001	-0,00002563	Trend (-)	-26926	<0.0001	-0,025	Trend (-)	-214	0,031	-6,461	Trend (-)
IX	-54595815	<0.0001	-0,00002645	Trend (-)	-56820	<0.0001	-0,027	Trend (-)	-427	<0.0001	-8,138	Trend (-)

Table 4.10: 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	-2960	<0.0001	-0,552	Trend (-)	-2950	<0.0001	-0,357	Trend (-)	-2597	<0.0001	-0	Trend (-)	-1450	<0.0001	-0,04	Trend (-)
IV	-4992	<0.0001	-0,675	Trend (-)	-5233	<0.0001	-0,611	Trend (-)	-5301	<0.0001	-0,2	Trend (-)	-3793	<0.0001	-0,115	Trend (-)
VI	-2339	<0.0001	-0,367	Trend (-)	-1737	<0.0001	-0,304	Trend (-)	-607	0,265	-0	No Trend	-839	0,123	-0,015	No Trend
VII	-1437	0,004	-0,236	Trend (-)	-1890	0	-0,217	Trend (-)	-2616	<0.0001	-0,1	Trend (-)	-1378	0,005	-0,043	No Trend
IX	-3460	<0.0001	-0,261	Trend (-)	-4118	<0.0001	-0,248	Trend (-)	-3964	<0.0001	-0,1	Trend (-)	-2931	<0.0001	-0,053	Trend (-)

Table 4.11: Results of the IHA analysis of the monthly flow rates and of maximum and minimum flows from the Cathedral Peak catchments

	Monthly Flow Rate (m3/sec)														
	Catchment III			**Catchment IV**			**Catchment VI**			**Catchment VII**			**Catchment IX**		
	Slope	**P value**	**Trend**	**Slope**	**P value**	**Trend**	**Slope**	**P value**	**Trend**	**Slope**	**P value**	**Trend**	**Slope**	**P value**	**Trend**
January	-0.0006982	0.1	No Trend	-0.00102	0.001	Trend (-)	-0.00021	0.25	No Trend	-0.0002045	0.1	No Trend	-0.00021	0.05	Trend (-)
February	-0.001077	0.05	Trend (-)	-0.00127	0.001	Trend (-)	-0.00036	0.25	No Trend	-0.0001584	0.5	No Trend	-0.00047	0.025	Trend (-)
March	-0.0006364	0.1	No Trend	-0.00118	0.001	Trend (-)	-0.00018	0.5	No Trend	-0.000144	0.5	No Trend	-0.00027	0.1	No Trend
April	-0.0005973	0.01	Trend (-)	-0.00071	0.001	Trend (-)	-0.00019	0.25	No Trend	-0.0001399	0.1	No Trend	-0.00019	0.025	Trend (-)
May	-0.000215	0.005	Trend (-)	-0.00035	0.001	Trend (-)	-8.66E-05	0.25	No Trend	-8.63E-05	0.005	Trend (-)	-9.84E-05	0.005	Trend (-)
June	-0.0001141	0.005	Trend (-)	-0.00023	0.001	Trend (-)	-3.22E-05	0.5	No Trend	-5.18E-05	0.001	Trend (-)	-6.42E-05	0.001	Trend (-)
July	-5.19E-05	0.25	No Trend	-0.00017	0.001	Trend (-)	-5.15E-06	0.5	No Trend	-3.81E-05	0.005	Trend (-)	-4.30E-05	0.001	Trend (-)
August	-1.90E-05	0.5	No Trend	-0.00013	0.001	Trend (-)	-6.65E-06	0.5	No Trend	-2.61E-05	0.025	Trend (-)	-3.06E-05	0.001	Trend (-)
September	-4.16E-05	0.5	No Trend	-0.00012	0.001	Trend (-)	-4.97E-05	0.25	No Trend	-6.62E-05	0.025	Trend (-)	-4.75E-05	0.005	Trend (-)
October	3.07E-05	0.5	No Trend	-9.01E-05	0.1	No Trend	-2.06E-05	0.5	No Trend	-1.74E-05	0.5	No Trend	-2.97E-05	0.5	No Trend
November	-0.0002815	0.25	No Trend	-0.00018	0.005	Trend (-)	-8.79E-05	0.025	Trend (-)	-8.07E-05	0.1	No Trend	-5.02E-05	0.05	Trend (-)
December	-0.0006316	0.025	Trend (-)	-0.00049	0.001	Trend (-)	-0.00019	0.005	Trend (-)	-0.0001163	0.1	No Trend	-0.00012	0.01	Trend (-)
	Maximum and minimum flows (m3/sec)														
	Catchment III			**Catchment IV**			**Catchment VI**			**Catchment VII**			**Catchment IX**		
	Slope	**P value**	**Trend**	**Slope**	**P value**	**Trend**	**Slope**	**P value**	**Trend**	**Slope**	**P value**	**Trend**	**Slope**	**P value**	**Trend**
1-day min	-1.92E-05	0.25	No Trend	-8.72E-05	0.001	Trend (-)	-3.49E-05	0.1	No Trend	-1.09E-05	0.05	Trend (-)	-1.53E-05	0.001	Trend (-)
3-day min	-1.95E-05	0.25	No Trend	-8.84E-05	0.001	Trend (-)	-3.38E-05	0.1	No Trend	-1.10E-05	0.1	No Trend	-1.53E-05	0.001	Trend (-)
7-day min	-2.03E-05	0.25	No Trend	-8.70E-05	0.001	Trend (-)	-3.38E-05	0.1	No Trend	-1.12E-05	0.1	No Trend	-1.57E-05	0.001	Trend (-)
30-day min	-1.64E-05	0.5	No Trend	-9.50E-05	0.001	Trend (-)	-2.30E-05	0.5	No Trend	-1.29E-05	0.1	No Trend	-1.76E-05	0.001	Trend (-)
90-day min	-1.57E-05	0.5	No Trend	-0.00011	0.001	Trend (-)	-2.26E-05	0.5	No Trend	-2.22E-05	0.025	Trend (-)	-2.42E-05	0.001	Trend (-)
1-day max	-0.002197	0.05	Trend (-)	-0.0026	0.01	Trend (-)	-5.43E-05	0.5	No Trend	-0.0003465	0.5	No Trend	-0.00089	0.05	Trend (-)
3-day max	-0.001957	0.05	Trend (-)	-0.00249	0.001	Trend (-)	-1.03E-05	0.5	No Trend	-0.0002841	0.5	No Trend	-0.00077	0.05	Trend (-)
7-day max	-0.001805	0.05	Trend (-)	-0.0024	0.001	Trend (-)	-0.00024	0.5	No Trend	-0.0002431	0.5	No Trend	-0.00066	0.05	Trend (-)
30-day max	-0.00133	0.025	Trend (-)	-0.00182	0.001	Trend (-)	-0.0003	0.5	No Trend	-0.0002308	0.5	No Trend	-0.00053	0.025	Trend (-)
90-day max	-0.0009649	0.01	Trend (-)	-0.00127	0.001	Trend (-)	-0.00024	0.25	No Trend	-0.000215	0.25	Trend (-)	-0.00037	0.01	Trend (-)

According to Burn and Hag Elnur (2002) and Kalumba *et al*. (2013), the terrestrial hydrological cycle is altered in different ways, depending on the change in various climatic factors such as rainfall and temperature. Small changes caused by climatic anomalies can have amplified effect on water recourses in 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 concluding that the changes evident in streamflow are due to climate, an analysis of the impacts on land use on the streamflow of the catchments is undertaken in Chapter 5.

4.3.2 Comparative analysis of the historical and current streamflow records

To date weirs IV, V, VI and VII have been re-established and streamflow monitoring has continued. 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 the 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 non-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 (Table 4.12) showed evidence of a significant decrease in the median monthly streamflow at Catchment IV for the entire year ranging between 0.2745 and 0.995 $m^3.sec^{-1}$per month. A significant decline ranging between 0.9 and 1 $m^3sec^{-1}$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 only slight differences between the historical and current period.

Table 4.12: Results of the IHA analysis of the median monthly, maximum and minimum flow rates from the Cathedral Peak catchment

Median Monthly Flows (m3/sec)									
	Catchment IV			**Catchment VI**			**Catchment 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 (m3/sec)									
	Significance Count	**Significance**	**Direction of change**	**Significance Count**	**Significance**	**Direction of change**	**Significance Count**	**Significance**	**Direction of change**
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

A significant decrease in the median monthly flow was evident for Catchment VI, ranging from 0.341 to 0.678 m^3sec^{-1} per month across the entire year. A significant decline was evident in the 1, 3, 7, 30 and 90-day minimum flows ranging from 0.702 to 0.904 m^3sec^{-1}, while the 1, 3, 7, 30 and 90-day maximum flows showed only slight differences between the two periods. A significant decrease in the median monthly flow was evident for Catchment VII, ranging between 0.006 and 0.325 m^3sec^{-1} per month, as well as significant declines ranging between 0.009 and 0.483 m^3sec^{-1} in the 1, 3, 7, 30 and 90-day minimum and maximum flows between the historical and current periods. The flow duration curves (Figure 4.2 - 4.4) further demonstrate the decreases in annual streamflows from the historical period to the current period for the three 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.

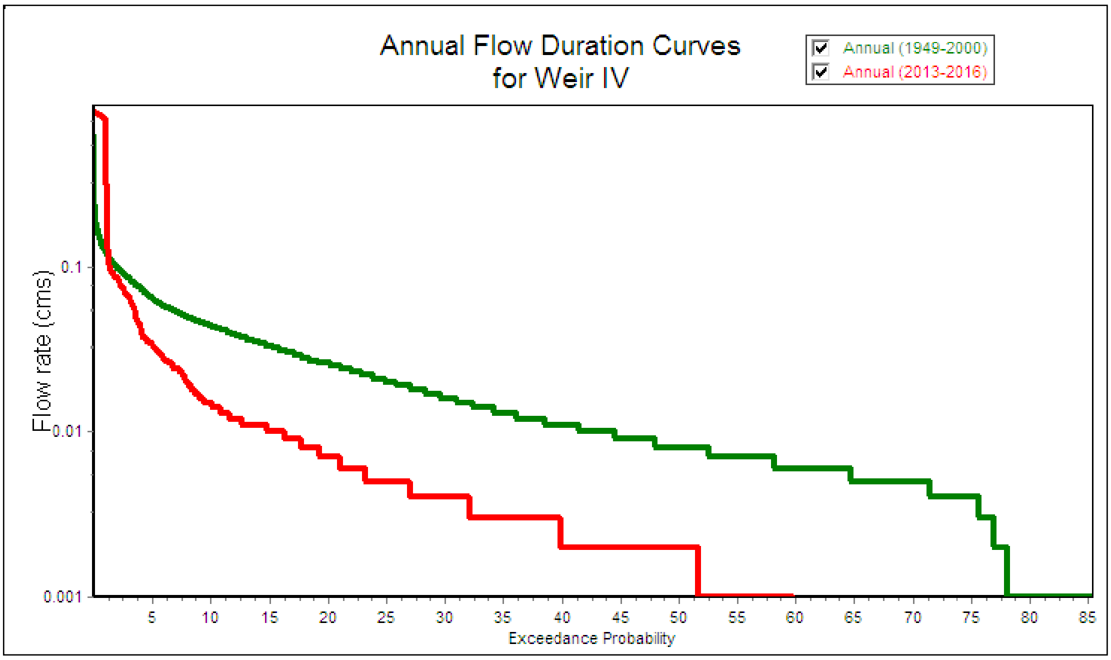

Figure 4.2: Annual flow duration curves for Catchment IV

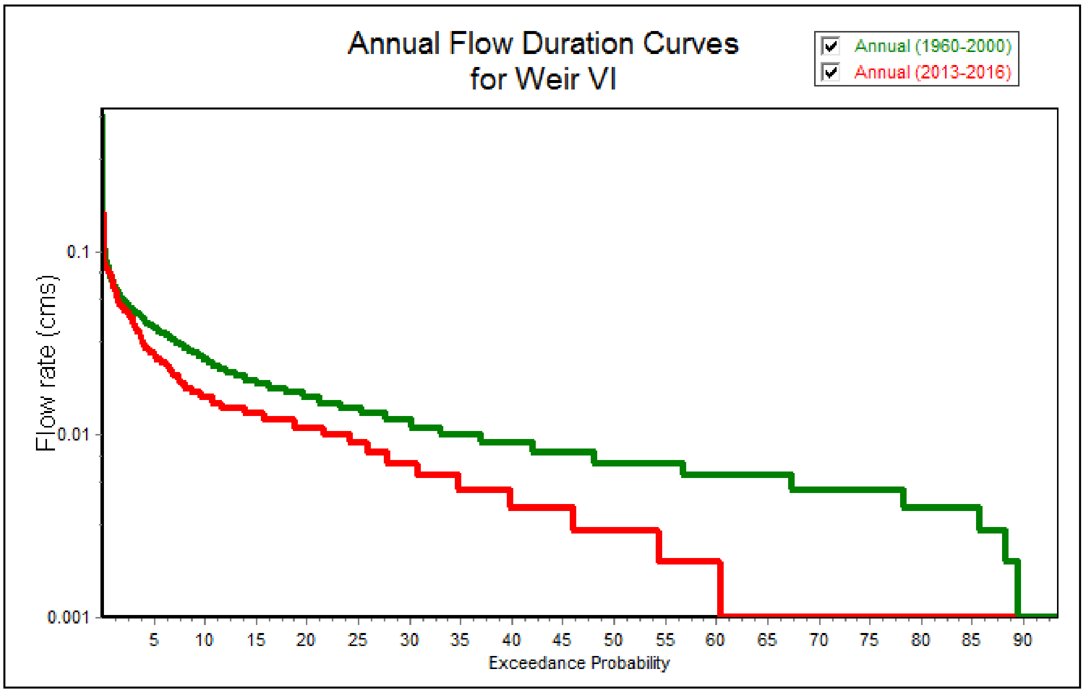

Figure 4.3: Annual flow duration curves for Catchment VI

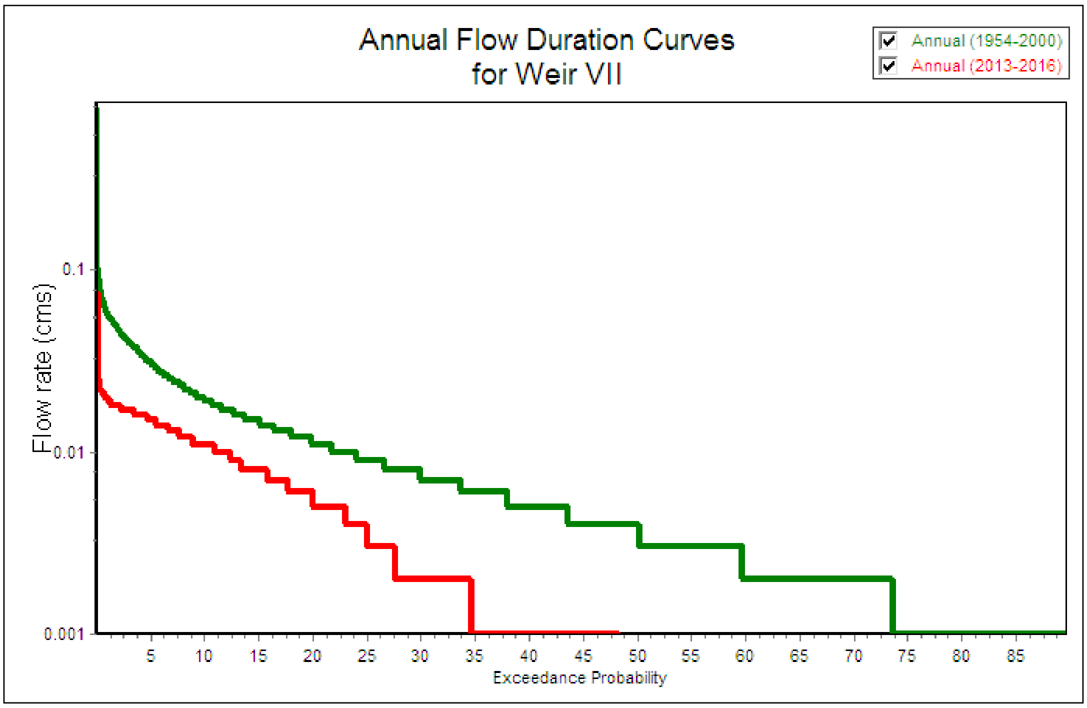

Figure 4.4: Annual flow duration curves for Catchment VII

5. ATTRIBUTION OF TRENDS

Given the streamflow trends shown in Chapter 4, the last stage of this study investigated whether the cause of these trends could be identified. According to Kormann *et al*. (2014) hydroclimatic changes observed in mountainous areas are twice as strong compared to the global average. However, literature also highlights that drastic changes in streamflow as a result of human activities such as land use change and river diversions have been observed since the mid-19th century (Zhang *et al*., 2014; Kormann *et al*., 2014). Thus, while statistical detection of change is important, it is critical to establish and understand the most likely cause of change in order to develop appropriate water management strategies and efficient long-term adaptation practices (Harringan *et al*., 2014). Understanding the causes of change allows water managers to apply evident based decision making and respond appropriately to the hydrological change. Therefore, the attribution of streamflow trends is important in this study as it will provide much needed information on the cause of decline in streamflow and begin to shed light on practical water management strategies in the Cathedral Peak region.

No comprehensive detection and attribution studies have been conducted in the Cathedral Peak region. However, studies by Scott (1999) and Nanni (1976) investigated the impacts of afforestation on water yield in the region showing strong declines in the streamflow, particularly the low flows due to the afforestation. Doyle and Barros (2011); Harringan *et al*. (2014) and Rabi *et al*. (2015) highlighted changes in rainfall and land use as the main drivers of streamflow alteration. Given that previous studies have shown the impact of afforestation but did not consider rainfall, this study investigated both the impacts of rainfall and land use as possible reasons for the decline in streamflow.

Of the catchments considered in the detection study, only Catchment III and VII were considered in the attribution study. The reasoning behind this is that besides Catchment IX these are the only catchments which underwent a land use change during the period of historical streamflow monitoring (1952 – 1993), with the remaining catchments considered to be in relatively pristine condition. Catchment IX was, and still remains, a fire exclusion catchment, thus over time it has become more woody but there are no records to show the progression of the increase of woody species in the catchment and therefore was not included.

Streamflow monitoring in Catchment III began in 1952. At this time the catchment treatment was biennial spring burns in uneven years (Figure 5.1). This continued until 1959 when the catchment was planted to and maintained as *Pinus patula* until 1981 when a wild fire burnt out the catchment (Figure 5.1). Following the fire, the catchment was planted to *Eragrostis curvula* and protected from fire.

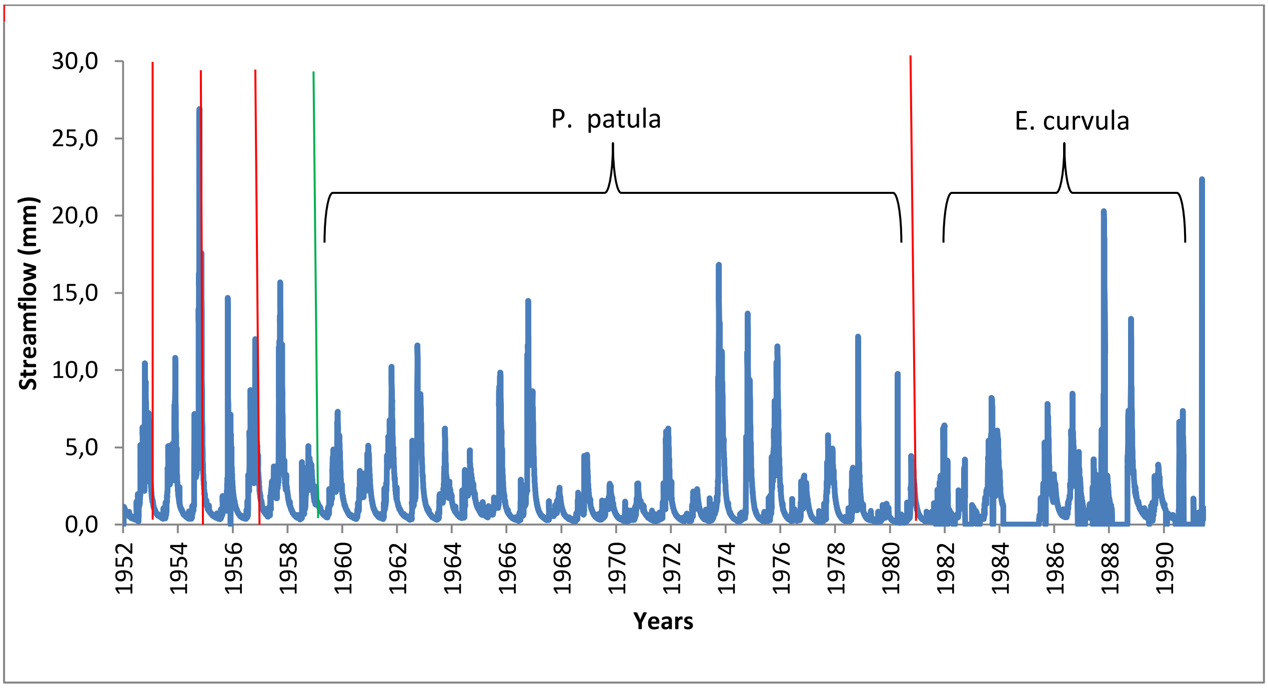

Figure 5.1: Observed historical streamflow for Catchment III with the changes in land use (green lines) indicated and the occurrence of fire (red lines)

Streamflow monitoring in Catchment VII began in 1957 while the catchment treatment was biennial spring burns in uneven years (Figure 5.2). In December 1966 the catchment was planted to *Pinus patula* and remained as such until an accidental fire in 1972. Thereafter the catchment was planted to *Eragrostis curvula* and protected from fire until an accidental fire in 1981. Following the fire, the catchment received biennial spring burns.

The influence of land use change on the streamflows of these catchments was first investigated, followed by the influence of rainfall on total streamflow during the historical period (1952 - 1993).

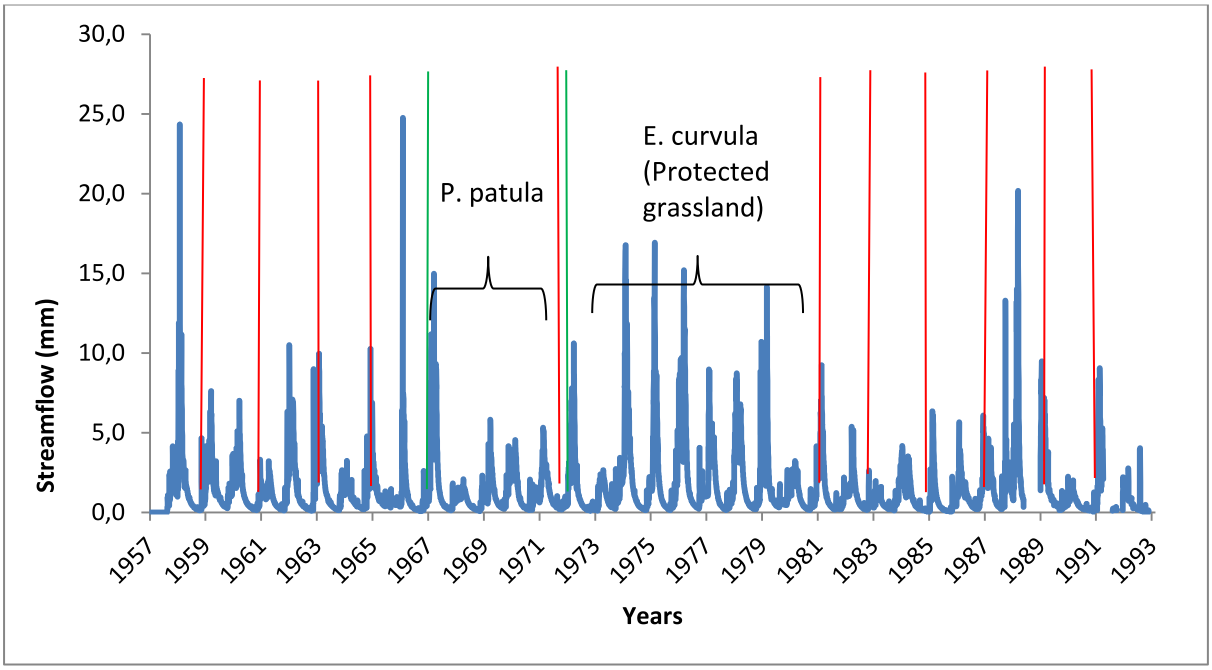

Figure 5.2: Observed historical streamflow for Catchment VII with the changes in land use (green lines) indicated and the occurrence of fire (red lines)

5.1 Influence of Land Use on the Streamflows of Catchments III and VII

To assess the impact of land use change on streamflow, an assessment of the streamflow under the different land uses for each catchment was undertaken using the IHA software. The observed streamflow record for each of the catchments was divided into three periods representing the catchment under natural grasslands, under *Pinus patula* and lastly under *Eragrostis curvula.* The non-parametric scorecard tables were calculated using the three periods of annual data to reveal a significance count which can be interpreted similarly to a p-value in non-parametric statistics as mentioned before in section 4.3.2.

A significant decline in streamflow across all months and for both low and high flows was shown for Catchment III following the land use change from natural grassland to *Pinus patula* (Table 5.1). Following the fire, the catchment was planted to *Eragrostis curvula*. Comparing the observed streamflows from the period where the catchment was under *Pinus patula* to the streamflows from when the catchment was under *Eragrostis curvula* shows increases in flows in all months except February – April, increases in high flows but continued declines in low flows. Given the low water use of *Erogrostis curvula* which was planted after the *Pinus patula*, increases in flows across the year including low flows were expected. Thus, it appears there is another influence on the streamflows beyond land use. The observed streamflows generated under natural grassland were compared to those generated under *Eragrostis curvula* as a final comparison. Although both are a grass species, significant declines in streamflow are evident under the *Eragrostis curvula* except in October and November. This also indicated a further influence on the streamflow beyond land use.

Table 5.1: Results of the IHA analysis of the monthly flow rate, minimum and maximum flows for the observed streamflow under different land uses in Catchment III

	Monthly flow rate ($m^3.sec^{-1}$)								
	Natural grassland VS *P. patula*			**P. patula VS *E. curvula***			**Natural grassland VS *E. curvula***		
	Significance Count	**Signif.**	**Direction of change**	**Significance Count**	**Signif.**	**Direction of change**	**Significance Count**	**Signif.**	**Direction of change**
January	0.3443	High	Negative	0.3704	High	Positive	0.5095	Low	Negative
February	0.6466	Low	Negative	0.9249	Low	Negative	0.5866	Low	Negative
March	0.3233	High	Negative	0.3423	High	Negative	0.2142	High	Negative
April	0.3353	High	Negative	0.5926	Low	Negative	0.1612	High	Negative
May	0.2022	High	Negative	0.7778	Low	Positive	0.1932	High	Negative
June	0.1381	High	Negative	0.7077	Low	Positive	0.2613	High	Negative
July	0.05506	High	Negative	0.9159	Low	Positive	0.1371	High	Negative
August	0.07708	High	Negative	0.2643	High	Positive	0.2042	High	Negative
September	0.1241	High	Negative	0.2192	High	Positive	0.07508	High	Negative
October	0.05506	High	Negative	0.02703	High	Positive	0.8408	Low	Positive
November	0.2492	High	Negative	0.05405	High	Positive	0.3724	High	Positive
December	0.05606	High	Negative	0.6436	Low	Positive	0.2843	High	Negative
	Maximum and minimum flows ($m^3.sec^{-1}$)								
1-day min	0.1932	High	Negative	0	High	Negative	0	High	Negative
7-day min	0.1942	High	Negative	0	High	Negative	0.05205	High	Negative
90-day min	0.2292	High	Negative	0	High	Negative	0.2743	High	Negative
1-day max	0.3834	High	Negative	0.8288	Low	Positive	0.2643	High	Negative
7-day max	0.1652	High	Negative	0.3073	High	Positive	0.3784	High	Negative
90-day max	0.2773	High	Negative	0.8869	Low	Positive	0.1421	High	Negative

The comparison of Catchment VII observed streamflows under natural grassland and *Pinus patula* was not as conclusive as those of Catchment III. Decreases in flows were evident for January, September, November and December as well as the 7-day minimum flow and all the high flows assessed (Table 5.2). Increases, however, were evident in the remaining months and the 1-day and 90-day minimum flows (Table 5.2). These results could be due to the short period (4 years) that the Catchment was planted to *Pinus patula* compared to 22 years in Catchment III thus the effects of *Pinus patula* in decreasing streamflow were not as severe as in Catchment III, which suggested that the decline in streamflow was influenced by factors beyond of land use change. Comparison of the observed flows under *Pinus patula* and *Eragrostis curvula*, shows a general increase in flows following the planting of the catchment to *Eragrostis curvula*. Similar to Catchment III, the comparison of streamflows under natural grassland to those under *Eragrostis curvula* showed significant declines in streamflow as well as the low and high flows. Again, indicating a further influence on the streamflow beyond land use.

Table 5.2: Results of the IHA analysis of the monthly flow rate, minimum and maximum flows for the observed streamflow under different land uses in Catchment VII

	Monthly flow rate ($m^3.sec^{-1}$)								
	Natural grassland VS *P. patula*			***P. patula* VS *E. curvula***			***E. curvula* VS Natural grassland**		
	Significance Count	**Signif.**	**Direction of change**	**Significance Count**	**Signif.**	**Direction of change**	**Significance Count**	**Signif.**	**Direction of change**
January	0.3904	High	Negative	0.02903	High	Positive	0.2913	High	Negative
February	0.6116	Low	Positive	0.05606	High	Positive	0.3904	High	Negative
March	0.967	Low	Positive	0.06306	High	Positive	0.3303	High	Negative
April	0.02102	High	Positive	0.7688	Low	Negative	0.09309	High	Negative
May	0.1552	High	Positive	0.8509	Low	Positive	0.03704	High	Negative
June	0.1622	High	Positive	0.5065	Low	Negative	0.05506	High	Negative
July	0.5245	Low	Positive	0.5626	Low	Negative	0.1962	High	Negative
August	0.4244	High	Positive	0.6667	Low	Positive	0.1912	High	Negative
September	0.6486	Low	Negative	0.2032	High	Positive	0.2462	High	Negative
October	0.8298	Low	Positive	0.05706	High	Positive	0.2613	High	Negative
November	0.2863	High	Negative	0.02002	High	Positive	0.1562	High	Negative
December	0.4605	High	Negative	0.03704	High	Positive	0.05405	High	Negative
	Maximum and minimum flow ($m^3.sec^{-1}$)								
1-day min	0.977	Low	Positive	0.2843	High	Positive	0.06707	High	Negative
7-day min	0.8088	Low	Negative	0.2302	High	Positive	0.3594	High	Negative
90-day min	0.8819	Low	Positive	0.1491	High	Positive	0.2733	High	Negative
1-day max	0.3353	High	Negative	0.06306	High	Positive	0.2603	High	Negative
7-day max	0.5696	Low	Negative	0.08208	High	Positive	0.3003	High	Negative
90-day max	0.6046	Low	Negative	0.0981	High	Positive	0.3103	High	Negative

5.2 Influence of Rainfall on the Streamflows of Catchments III and VII

To assess the influence of rainfall in the decline of streamflow the rainfall from each individual period where the land use changed was tested for a trend to evaluate if the trend detected in the rainfall correlated with the negative trends detected for streamflow. In the case of Catchment III the historical rainfall was separated for natural grassland (1952-1958), *Pinus patula* (1959 - 1981) and *Eragrostis curvula* (1982 - 1991) and for Catchment VII the rainfall was separated for natural grassland (1957 - 1966), *Pinus patula* (1967 - 1972), *Eragrostis curvula* (1973 - 1993). The analysis involved the evaluation of rainfall trends against the negative streamflow trends for the individual periods during which changes in land use had occurred. Correlations between the trends gave an indication of the role of rainfall as a factor that may be attributed to the decline in streamflow.

The results obtained from the rainfall analysis (Tables 5.3 and 5.4) show that no trends were detected in rainfall during the different land uses which may suggest that rainfall had no influence on the decline in streamflow in Catchment III.

However, significant negative trends were detected in the rainfall from Catchment VII (Table 5.4) which correlates with the streamflow trends detected in Chapter 4. This consistent decline in rainfall which follows a similar trend as the streamflow, therefore, begins to indicate that the decline in streamflow during this time may possibly be as a result of decline in rainfall.

Table 5.3: Rainfall trends from Catchment III during different land uses

	Catchment III				
	Years	**MK Test (S)**	**P value**	**Sen's Slope**	**Trend**
Natural grassland	1952-1958	62174	0.084	0	No Trend
P. patula	1959-1981	341650	0.143	0.0001374	No Trend
E. curvula	1982-1990	144	0.998	0	No Trend
Overall Trend	1950-1990	-499797,0	0,353	0,000085	No Trend

Table 5.4 Rainfall trends from Catchment VII during different land uses

	Catchment VII				
	Years	**MK Test (S)**	**P value**	**Sen's Slope**	**Trend**
Natural Grassland	1957-1966	-173973	0.011	0	Trend (-)
P. patula	1967-1972	-92408	0.004	0	Trend (-)
E. curvula	1973-1993	-2413410	<0.0001	0	Trend (-)
Overall Trend	1954-1993	-9576092,0	< 0.0001	0,000046	Trend (-)

The overall results from the attribution study have identified and indicated that both land use change and rainfall have a noticeable impact or influence on streamflow. The impact of land use was evident in Catchment III with the persistent decline in streamflow following the planting of *Eragrostis curvula* used for rehabilitation after the removal of *Pinus patula* from the fire. Furthermore, the investigation on the influence of rainfall shows no indication that the decline in streamflow could be as a result of rainfall as there were no trends detected in the rainfall during the investigation period. In Catchment VII the decline in rainfall has been identified as the main cause of the decline in streamflow. This reasoning comes from the investigation of land use which indicated that even with the afforestation of *Pinus patula*, which was relatively short, there was an influence on streamflow beyond land use and further investigation of the rainfall showed that there was a consistent decline in rainfall during the investigation period, thus indicating that the decline in rainfall had an influence beyond land use change.

6. DISCUSSION

The importance of temperature, rainfall and streamflow has been discussed extensively in the literature. Many climatic and hydrological studies recognize these variables as key indicators of change in the hydrological cycle particularly in high altitude areas (Burn and Hag Elnur, 2002; Buytaert *et al*., 2006; Hamed, 2008; Caloiero *et al*., 2011; McGuire *et al*., 2012; Kalumba *et al*., 2013). Advances in mountain climate research indicate that high altitude regions are vulnerable and highly sensitive to the impacts of climate change (Rangwala and Miller, 2010; Behnke, 2011; McGuire *et al*., 2012). Historical trend detection and attribution studies are regarded as useful tools in climate change research as they provide a better understanding of the sensitivity and responses of the high altitude environments which can be used as early detection signals for global change impacts (IPCC, 2013). The lack of data due to the paucity of observation stations and the complex terrain in mountainous regions continues to restrict the number of studies conducted. As a result insufficient attention is given to and not much is known about long-term temporal trends of hydroclimatic variables in these regions (Barry, 1992; McGuire *et al*., 2012). However, for this study the available long term dataset has allowed for the analysis of long term trends in the historical records from the Cathedral Peak region. The section presented below will discuss the results obtained from the detection and attribution study.

6.1 Changes in the Climate and Streamflow Response of the Cathedral Peak Catchments

According to Coats (2010) and Wu *et al*. (2014) the impacts of climate change are non-uniform and vary from region to region however, on a global scale the general pattern of climate change has been well documented and is no longer questionable. In a summary study, Barnett *et al*. (1999) reported a general consensus that the observed changes in the global mean annual surface temperature over the last century were unlikely to be as a result of natural variability alone, therefore suggesting anthropogenic forcing. Several studies thereafter including those by the IPCC (2007; 2013) have also demonstrated that the increased greenhouse emissions have begun to alter the earth’s climate, by changing the global average temperature (Kusangaya *et al*., 2013; Wu *et al*., 2014). In the literature reviewed, several studies from different parts of the world noted an observed increase in the average global temperature of approximately 0.6°C since the beginning of the twentieth century and 0.3°C from the mid-century (Easterling *et al*., 2000; Zhang *et al*., 2000; Feidas *et al*., 2004; Mohsin and Gough, 2010; Kruger and Sekele, 2013; IPCC, 2013). Rising temperatures have displayed positive trends in minimum temperatures, extreme minimum temperatures and a decreasing diurnal temperature range (Zhang *et al*., 2000; Mohsin and Gough, 2006; Kruger and Sekele, 2013). Studies by Hulme (1996); Mason and Jury (1997); Kruger and Shongwe (2004); New *et al*. (2006) and Kruger and Sekele (2013) found similar warming trends for southern Africa. While regional studies in South Africa by Kruger and Shongwe (2004) and Tshiala *et al*. (2011) have also observed increases in temperature and alluded that the altering of atmospheric composition of gases in the air has led to increased temperatures. Hulme *et al*. (1996) showed a decrease in the diurnal temperature range as a result of a decrease in minimum temperatures during the 1950s and 1960s, while Easterling (2000) found increases in the annual mean daily maximum temperatures and widespread increases and some decreases in the annual mean daily minimum temperatures. Results from Kruger and Shongwe (2004) correspond with reported increases in temperature having found significant increases in annual mean temperatures with the strong warming detected for the interior of South Africa during autumn months.

Analysis of the temperature records from the Cathedral Peak area show warming trends, which concur with results obtained from previous studies. The consistent positive warming trends detected for the daily maximum and average temperature at all three stations considered for the study agree with the trends observed in the literature. The negative trend detected for frost at the Cathedral Peak forest station begins to support the observed decrease in extreme minimum temperatures. Assessment of the seasonal temperatures showed statistically significant warming trends in the summer months at all three stations indicating that summers over the historical period have been getting hotter, which supports the general observation of a gradual increase in temperature. Furthermore, statistically significant positive trends were found in winter, indicating that winter temperatures between 1955 and 2000 have been warming at the Office meteorological and Cathedral Peak forest stations. A considerable emphasis has been placed on creating awareness of the potential impacts that increased temperatures will have on the rates and distribution of actual and potential evapotranspiration and soil moisture which will intensify the hydrological cycle and have detrimental impacts on agriculture, human wellbeing and environmental health (Wu *et al*., 2014).

The regional and local impacts of climate change are still debatable and surrounded by uncertainty regarding the occurrence and magnitude of change (Nicholls, 2006). Clarvis *et al*. (2014) has emphasized that there are a number of sources and types of uncertainties which restrict our ability to understand and make informed decisions about climate change and variability in the hydrological context. A key constraint in this study was the difference in the length of data between the historical and current periods which restricted the comparative analysis resulting in a number of inconclusive results, which made it difficult to establish and interpret the trends with certainty. Despite this shortfall the results showed positive differences for the temperature threshold events, which indicated warming trends between the historical and current periods. Positive differences detected in the number of days with temperatures exceeding 30^{o}C and 35^{o}C further support the observation of a gradual increase in the temperature. These results correlate with temperature trends observed for South Africa at a national scale although there have been no studies specifically addressing temperature changes in high altitude areas, the results agree with temperature trends observed in studies by Mason and Jury (1997) and Shongwe and Kruger (2004). These results also agree with the global trends observed for temperature as reported in the literature and the general consensus of increasing temperatures. This begins to indicate that, the detected increases in the temperature distinctly speak to the impacts of global climate change.

In the literature, mountainous areas are recognised for their importance in the provision of several ecosystems goods and services, particularly the provision of water (Beniston and Stoffel, 2014). The shift in the climatic and hydrological trends of mountainous regions has been observed with predictions of future warming trends forecast to affect mountainous regions more intensely, thus placing a threat on the highly sensitive and vulnerable ecosystem (Clarvis *et al*., 2014). These changes will effectively bring challenges to the ways in which water is allocated and governed which directly influences the management and strategic planning of water resources to ensure water security in the future (Clarvis *et al*., 2014).

Rainfall patterns are non-uniform across the globe (Duhan and Panday, 2013; Burn and Hag Elnur, 2002). There is no general consensus on global rainfall trends as different regions experience changes of varying magnitude thus rainfall trends are often clouded by uncertainty (Clarvis *et al*., 2014; MacKellar *et al*., 2014). Various authors have highlighted the issue of uncertainty with regards to rainfall trends and the difficulty in planning for the expected climate change impacts given the high temporal and spatial variability of rainfall across southern Africa (Nel and Sunmer, 2006; Nel, 2009; Jury, 2013). With this said, studies from southern Africa have observed a decline in rainfall since 1961. Studies from the literature have reported negative trends in rainfall for Zimbabwe, Malawi, Zambia and Botswana dating back to the 1950's while similar results were obtained for South Africa from studies by Mason and Jury (1997). Beyond investigating annual rainfall trends, other studies by Mason *et al*. (1999); Groisman *et al*. (2005); Kruger (2006); New *et al*. (2006), examined the occurrence of heavy and extreme rainfall events and found evidence of significant increases in the frequency of high and extreme rainfall events and related indices over south western and eastern South Africa, southern Free State and parts of the Eastern Cape.

The statistically significant trends detected in the Cathedral Peak rainfall data are in line with the trends detected from previous studies also showing negative trends. Strong negative trends were detected in the daily rainfall records, fewer were detected in the monthly records and no trends were detected in the annual data. The aggregating of the daily rainfall values may have reduced the variability in the extreme daily rainfall events consequently obscuring the trends which explains the decrease in trends detected in the monthly and annual data. Long-term trends in temperature indices are often more noticeable than rainfall changes (MacKellar *et al*., 2014). This is evident in the study as fewer significant trends were detected in the rainfall records when compared to temperature. The inability to detect statistically significant trends in the rainfall could be possibly due to a small change in the rainfall between 1948 and 1993 relative to the natural variability, which may have been greater than the actual trend (Nicholls, 2006). In the seasonal analysis, autumn was found to have the most statistically significant trends, all of which were negative, indicating a decline in autumn rainfall while the other seasons displayed no significant trends. Even though there is a low count of significant negative trends across the temporal scales (daily, monthly and seasonal) the overall results continue to indicate a decline in the historical rainfall in the Cathedral Peak research catchments over the period 1948 – 1993.

The IPCC (2007) report indicated that rainfall changes have intensified across the world and will continue to do so post 2000. Furthermore, temporal and spatial variability has been well documented in literature with many authors reporting increased variability in rainfall for southern Africa (Mason *et al*., 1999; Kalumba *et al*., 2013). The comparative analysis showed a few significant differences, however, the differences detected between the historical and current data differed from the historical trends as they showed increases in the number of large rainfall events. Notable increases in the 20 and 30 mm thresholds indicated an increase in large and extreme rainfall events between the historical and current periods. Rainfall trends from the comparative analysis are consistent with trends observed at national scale and further support the results obtained by Mason *et al*. (1999) and subsequent studies which reported significant increases in rainfall and extreme events. Additionally these increases begin to agree with the global rainfall predictions by the IPCC (2007) which forecast the intensification of large rainfall events as a result of global climate change. The detection of increased large and extreme rainfall events and the overall decrease in rainfall in the Cathedral Peak region is anticipated to have an impact on the intensity of floods and occurrence of droughts in the immediate surrounding areas as well as South Africa as a whole. Thus, risk and vulnerability assessments are vital to carefully evaluate the water availability and prepare for the possible impacts on the Cathedral Peak.

There is no general consensus on streamflow trends on a global scale. According to Gautam *et al*. (2010) majority of streamflow studies are conducted in the northern hemisphere where snow melt is the key driver in streamflow generation. For this reason not much is known about streamflow trends in the developing countries of southern Africa and there is a perception that mountainous regions have little or no impact at a global scale. However, of the streamflow studies undertaken, characteristics such as variability and the relationship between rainfall and streamflow have been common areas of study. Results from Fanta *et al*. (2001) showed no significant trends at the majority of gauging stations that were investigated in nine countries across southern Africa. Sene *et al*. (1998) also found evidence of a strong relationship between rainfall and streamflow however, similar to other studies conducted in southern Africa no significant long-term trends were detected. For South Africa, Odiyo *et al*. (2011) found evidence of a strong relationship between rainfall and streamflow on an annual basis in the Luvuvhu river catchment; increased variability in both rainfall and streamflow were reported but no significant trends were evident. Despite the lack of significant trends observed from previous studies, the data available for this study allowed for the establishment of statistically detectable trends.

Significant negative trends in the daily, monthly, seasonal and annual streamflow records showed a strong evidence of a decline in streamflow between 1949 and 2000. Catchment VI showed the fewest trends. Further analysis of the historical streamflow using the IHA software also showed negative trends. The results from the comparative analysis are in line with the historical results and show a continued decline in streamflow between the historical and current period. The observed decline in streamflow speaks to changes detected in the temperature and rainfall as literature reveals and that the terrestrial hydrological cycle is altered in different ways depending on the changes in various climatic factors such as rainfall and temperature. The decline in streamflow appears to correlate with the general decline in rainfall and is in agreement with reports of increased variability and shows evidence of a strong relationship between rainfall and streamflow as suggested by Sene *et al*. (1998) and Odiyo *et al*. (2011) in previous studies. The observed decline in streamflow in the Cathedral Peak area further highlights the decline in water availability and the threat of water scarcity in South Africa as it is a semi-arid region (Nel and Sunmer, 2006). This speaks to the necessity of proper planning and adaptation strategies which need to be put in place in order to be able to deal with water management issues in the best way possible (Wu *et al*., 2014). Although there is no general consensus on streamflow trends in lowlands and high altitude regions in the literature the observed negative trends indicate a definite decline in streamflow in the Cathedral Peak area.

Although results from the rainfall historical record displayed a few statistically significant rainfall trends, continuation of the study investigating the differences between the historical and current rainfall record began to show stronger and more distinct trends that are statistically detectable and possibly attributed to climate change. The trends in streamflow and temperature were statistically detectable in both historical and comparative analysis and indicated definite trends respectively. A major shortfall for the comparative analysis was the lack of current data as monitoring in the catchments was discontinued shortly after 1994. However, it must be mentioned that the Cathedral Peak area has a high density observation network which is favourable for trend detection. And with continued monitoring and data collection the changes noted by the IPCC (2013) in the 2000's may be detected using longer current data.

6.2 Understanding the Cause of the Observed Trends

The vast majority of climate science studies investigate the occurrence of trends which leaves uncertainty about the driving force causing the change (Clarvis *et al*., 2014). The uncertainty restricts the level of confidence in the results and the decision making process because of the lack of knowledge on the significance and magnitude of the trends (Nicholls, 2006). Harringan *et al*. (2014) also emphasizes that although detection of trends is important, finding out the cause of the change is essential for proper planning and the implementation of efficient and sustainable water management practises. Evidence of changes in rainfall and landuse have been demonstrated in the literature as the key drivers in the altering of the hydrological cycle (Wu *et al*., 2014). The impacts of climate change are likely to be characterized by the variations in climatic factors such as precipitation, air temperature, potential and actual evapotranspiration resulting in the intensification of the terrestrial hydrological cycle (Wu *et al*., 2014). In addition to climatic factors, land use change and land management practices have also been noted to have noticeable impacts on water resources (Muñoz-Arriola *et al*., 2009; Wagner *et al*., 2013). The conversion of natural land for agriculture and timber production are highlighted as primary forms of global land use change and significant drivers of change in surface water and energy balances (Muñoz-Arriola *et al*., 2009; Stonestrom *et al*., 2009). In order to identify and understand the possible factors causing the decline in streamflow, the attribution study undertaken investigated the influence of rainfall and land use as key agents of hydrological alteration.

The anticipated effect of afforestation in both Catchments III and VII was evident in the negative trends indicating the decline in streamflow and the subsequent changes in rainfall and land use also became noticeable. For Catchment VII the consistent decrease in rainfall over the historical period was identified as the main cause attributed to the decline in streamflow which begins to support the observations from the literature and is in line with reports showing evidence of a strong relationship between rainfall and streamflow. The decline in rainfall and streamflow pose a threat to water availability and reiterates the importance of effective water governance and management in head water catchments such the Cathedral Peak to ensure water security in the future (Clarvis *et al*., 2014).

The results for Catchment III identified land use change as a key driver in the alteration of the hydrology of the catchment largely contributing to the decrease in streamflow. The afforestation of Catchment III initiated the decline in streamflow however, the subsequent effects of the fire and degradation were evident in the continued decline. Changes in land use alter the soil infiltration, evapotranspiration and subsequent soil hydraulic processes which impact on surface hydrology (Muñoz-Arriola *et al*., 2009; Zheng *et al*., 2009). This is evident in the results from the attribution study as the extensive afforestation of Catchment III appears to have led to degradation of the land and even with rehabilitation interventions by planting of *Erogrostis curvula* the changes to the land are seen to have prolonged impacts on the streamflow. This observation from the attribution study highlights issues of land use change and management practises placing emphasis on the need to develop interventions to reduce land degradation. Zheng *et al*. (2009) and Stonestrom *et al*. (2009) have noted the widespread and direct impacts of land use change and climate change highlighting the importance of understanding the complex and dynamic interaction between land use and climate change. In particular to head water catchments such as Cathedral Peak the changes in land use combined with the decrease in rainfall detected pose a challenge in ensuring water security for all social, economic and environmental purposes in the future.

6.3 Uncertainties and Challenges encountered

The challenges faced during this study revolve around the data quality and the length of data, although in relative terms the data used in this study was of a satisfactory standard. MacKellar *et al*. (2014) noted that South Africa has a reasonably good rainfall and temperature network which makes it possible to conduct long-term investigations of trends and variability across several decades. However, for many studies, especially in developing countries the lack of good quality data remains an obstacle. Furthermore, there is the perception of mountainous region having little or no impact on a global scale. This has ultimately led to the neglect of mountainous regions in research studies. As a result not much is known and there remains uncertainty about hydroclimatic trends in rainfed, high altitude regions in southern Africa and shifts in long term baseline conditions (Gautam *et al*., 2010).

Literature reveals that there are several sources of uncertainty which can be characterised into four types namely natural variability, incomplete knowledge, decision-rule uncertainty and human element (Knoesen, 2011).

The challenges incurred during this study broadly encompassed all four sources of uncertainty. The main challenge primarily stemmed from incomplete and short data records, which required the data to be patched in order to compile data records that were suitable for analysis. This is incomplete knowledge and refers to data uncertainty in situations where there is a lack of sound theoretic and empirical knowledge which limits the understanding of what researchers have the potential of knowing (Knoesen, 2011). In this study the incomplete data in some instances may have restricted the detection of significant trends and potentially lead to inadequate knowledge of trends and their interpretation. The lack of available current streamflow data limited this study to only consider three of the five catchments used in this study, which may have skewed the results as a small sample of data was used to represent the study area and an even larger mountain region. Furthermore, the current drought conditions may have distorted the results from the comparative analysis because of the lower streamflow and rainfall recorded as a result of the dry spell. Incomplete knowledge also includes model uncertainty, which arises from modelling methods and procedures used in research (Knoesen, 2011). The use of models highlights the uncertainty as a result of human element, which is open to human error if there is a lack of understanding of the model operations and subjectivity in the model chosen due to personal preference. Although, the methods used to patch the rainfall data had been extensively investigated and used in previous studies, and the model used to extend the streamflow was configured and verified for this specific study however, one cannot rule out the uncertainty in patched data. Natural variability is an inherent challenge in climate change studies which raises uncertainty about the trends detected and affects the confidence with which the results can be used (Abdul Aziz and Burn, 2006; Knoesen, 2011; Beniston *et al.*, 2014). For this reason it is important to use adequate and complete long-term data to ensure accurate detection and establishment of trends (Kundezwicz and Robson, 2000; Dixon *et al.*, 2006)

An important part in trend detection studies is the use and application of the results obtained. The use of results obtained from a representative area such as the Cathedral Peak research catchments can raise uncertainty as they are a sample of the greater study area thus requiring up scaling (Knoesen, 2011). In this regard uncertainty can come from a lack of understanding of the microclimate dynamics in high altitude regions as several authors have noted that this area of research has not been given the necessary theoretical attention because of limited data as a result of lack of observation networks (Barry, 1992; Gautam *et al*., 2010; McGuire *et al*., 2012). This leads to the inability to understand how the detected trends and changes in climatic variables translate to a larger scale, thus highlighting the importance of conducting more studies in high altitude regions to gain better understanding of trends in mountainous regions (Beniston, 2010). The benefit of doing this cautions against the incorrect use of results so as to ensure the accurate interpretation of trends in order to make well informed decisions about the future of the country's water resources.

Despite the limitations caused by missing data records, modelling and uncertainty of natural variability in this study, the statistical tests together with the available data have begun to show early signals of change attributed to the onset of climate change impacts observed over the last fifty to sixty years.

7. CONCLUSION

Significant progress in mountain climate research has been made since the 1950's. Key questions relating to changes in mountain climate concerning the direction of change, whether or not the changes are comparable in magnitude and timing to those in the lowlands, and across the continent are slowly being answered (IPCC, 2013). Recent advances in research have emphasised the importance of understanding mountain responses to climate change impacts as these will have direct and indirect impacts on water resources management and planning (Thorne and Woo, 2011). Advances in technology such as the introduction of automated weather stations have permitted more stations, expanding observation networks and thus increasing the amount of data available and allowing for more detailed studies to be conducted in mountainous regions.

7.1 Main Findings of the Study

The main objective addressed in this study was to detect trends in the historical temperature, rainfall and streamflow records guided by the following aims:

- Detect trends and changes in the temperature, rainfall and streamflow historical records from the Cathedral Peak catchments
- Detect changes and any noticeable differences between the current and historical temperature, rainfall and streamflow records
- Determine if these trends correlate with those observed at national scale
- Investigate possible causes and explanations for the changes detected

The results of the detection study have shown significant positive trends in the temperature and significant negative trends in streamflow data while a few positive rainfall trends were detected. Results of comparative analysis correlated with those observed from the detection study indicate an increase in temperature, a decline in rainfall and streamflow between the historical and current period. Furthermore the results obtained from the detection study supported the trends detected at national scale from previous studies and attest to the IPCC (2007) reports that climate change has become greater and more pronounced in recent studies giving an indication that noticeable historical trends may be few however, current records may reveal stronger and more significant trends post 2000. Possible causes for the decline in streamflow identified rainfall and land use as key drivers of change in Catchments III and VII in the Cathedral peak region. Climate change impacts are widely discussed in the literature with many authors concluding that the shifts in climatic trends will drastically alter the hydrological cycle consequently calling for innovative water management strategies (Clarvis *et al.*, 2014).

7.2 Implications for Water Resources Management

In climate science the study of long term trends and comparison of either observed and simulated or past and present data has become common practice in information gathering and the evaluation of persistent changes in the observed climate and understanding whether the change is driven by natural climate variability or external forcing (Liu and Xia, 2010). In the field of hydrology and water resources research this assists in understanding the mechanisms and causes of global change and its impacts on the various aspects of the hydrological cycle allowing climate scientists and policy makers to take well informed decisions about the strategic management and planning of water resources in the future (Liu and Xia, 2010; Wu *et al.*, 2014). Changes in precipitation and temperature will have direct impacts on streamflow and the added impacts of land use to this will further alter the surface hydrology. Given that the impacts of internal and anthropogenic forcing will continue to affect future climate leaving sensitive ecosystems, communities and economies under threat, it is crucial to detect early change signals to allow us to prepare for and mitigate the impacts where possible (Nicholls, 2006). The results obtained for the Cathedral Peak region from both detection and attribution show that climate change and land use are undeniably linked, furthermore the results begin to highlight the possible threats that the Cathedral Peak region is faced as primary source of water for environmental, social and economic use in KwaZulu-Natal and Gauteng. The detected changes in the hydroclimatic highlight the threats posed to this sensitive and vulnerable ecosystem.

The impacts brought on by climate change will present major shifts in the baseline hydroclimatic conditions and significantly increase uncertainty that water managers need to account for and integrate in water resources management and planning (Clarvis *et al.*, 2014). The decrease in rainfall and streamflow together with the increased temperature detected for the Cathedral Peak region are set to affect not only the mountain area but also the surrounding and downstream communities and ecosystems of KwaZulu-Natal and more importantly the Gauteng industries that are exposed and vulnerable to these changes (Nel and Sunmer, 2006). These results emphasize the reality of climate change and the threats it stands to pose on the country's most valuable water source which generates 25% of South Africa’s runoff and contributes significantly to the country’s economy (Nel, 2009; Nel and Sunmer, 2006). The decline in the rainfall and streamflow regime of the Cathedral Peak region stand to jeopardise the domestic, agriculture and most importantly economic activities in Gauteng which largely depend on the water transferred through the inter-basin transfer scheme (Nel, 2009; Lewis and Oosthuizen, 2014). Although a decline in historical rainfall trends was detected, the comparative analysis revealed an increase in heavy and extreme rainfall, which may require improved infrastructural development for urban and metropolitan areas in order to cope with the increased frequency and occurrence of heavy rainfall.

Ecosystems based adaptation strategies may be needed for downstream communities in KwaZulu-Natal in order to build resilience and reduce the harmful effects of climate change. Ecosystems services provided by wetlands and natural vegetation can create useful natural buffers offering protection from flooding and soil erosion caused by heavy and extreme rainfall hence ecosystems based adaptation should be encouraged in vulnerable and rural communities (Lewis and Oosthuizen, 2014). Environmental and land degradation brought on by changes in rainfall and land use practices also stand to impact the rural livelihoods of the downstream communities who depend on dry land farming and the surrounding natural resources for food, shelter, firewood and water (Lewis and Oosthuizen, 2014).

On a larger scale the changes detected in this study have begun to show the impacts of climate change. The implications of the decline in rainfall and streamflow will translate into a decline in available water, which will require innovative and effective water management and governance. This will mean that water managers and decision makers may be faced with the task of revising the traditional methods and tools that have been used to meet water demand (Wu *et al.*, 2014; Clarvis *et al.*, 2014). The changes in water availability will have to be considered and further inform the water management policies and frameworks that are put in place in order to address issues of capacity building, adaptive management and mitigation in efforts to increase the resilience and coping mechanisms of vulnerable communities, all while ensuring water supply and security in the future (Lewis and Oosthuizen, 2014).

7.3 Recommendations

Future research in high altitude regions relies heavily on the availability of sufficient good quality data. Therefore, expansion of the observation networks and monitoring is necessary for the collection of data. Gaining in depth knowledge of the climate change impacts on hydroclimatic variables in mountainous regions will require more detailed studies focusing less on variability but rather, the occurrence and magnitude of long term trends in these regions to accurately assess the extent to which the variables are affected. Furthermore, the studies conducted must also begin to investigate the causes and factors giving rise to the trends. This knowledge is vital to for making well informed decisions for water resources management.

Small catchments in mountains regions must no longer be thought of as having little or no impact on the global scale as studies have begun to show their vulnerability and sensitivity to climate change as well as their value in providing early warning signals.

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