SCHOOL OF ENVIRONMENTAL SCIENCES

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Impacts of greenhouse gases from coal power stations on climatic trends in Witbank area, South Africa

BY

Mafamadi M.A (11582289)

Supervisor: Prof J.O. Odiyo

Co-Supervisor: Ms R. Makungo

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DECLARATION

I, Mercia Aluwani Mafamadi, declare that this research is my own work and is submitted to the department of Hydrology and Water Resources at University of Venda, for fulfillment of a Masters degree of Earth Sciences in Hydrology and Water Resources and it has not been previously submitted by me or any other person for any degree in any instituition/ university.

Signature………………… Date………………..

ABSTRACT

Greenhouse gases (GHGs) from coal power station affect the behaviour of climatic parameters such as the temperature, rainfall and evaporation, over a long period of time, hence causing climatic trends. This study focused on investigating the impacts of Greenhouse gases (GHGs) from coal power stations on climatic and hydrological trends in Witbank area. To accomplish this, linear regression (LR) and Mann-Kendall (MK) trend test were used to detect the hydro-climatic trends and their significance. GHG emissions were obtained from Eskom's sustainability report on the Eskom website. Temperature data for the years 1950-2000 and 1993-2016 and rainfall data for the years 1925-2000 and 1993-2016 were used. Double Mass Analysis (DMA) was used to check the homogeneity and consistency of temperature and rainfall data from South African Weather Services (SAWS) station with the Lynch database and Water Research Commission (WRC) data. Data was patched and extended using LR where necessary. Trends in temperature, precipitation and flow were assessed using MK trend test and LR based on monthly, seasonal, and annual scales. GHG emissions were compared with the hydro-climatic data over time in order to detect the impacts of GHG emissions on temperature, rainfall and streamflow. The MK results indicated that GHG emissions had some impacts on temperature with statistically significant increase in annual, monthly and seasonal time scales for the period 1950-2016. LR also produced the same results for annual temperature. Monthly and seasonal temperature could not be produced with the LR method because of data gaps. The MK and LR models produced similar results, indicating that there was a non-significant increase in temperature before coal power stations were introduced (1950-1974) and a significant increase in temperature after the commissioning of coal power stations (1975-2016). MK and LR also produced the same results for annual rainfall data, indicating that there was a significant increase in rainfall before coal power stations were introduced (1925-1974) and a non-significant increase after the commissioning of coal power stations (1975-2016). For monthly time scales MK and LR indicated increasing and decreasing trends before and after coal power stations were introduced. MK and LR results for streamflow stations B2H004 and B2H007 showed similar results indicating non-significant increase in annual and seasonal streamflow, but differed in monthly streamflow where MK showed significant increases whilst LR showed non-significant trends. The study concluded that GHGs from coal power stations had significant impacts on the hydro-climatic trends in Witbank area. GHGs from coal power stations caused significant increase in temperature as temperature increased by 3.7°C after coal power stations were introduced, whereas temperature had increased by 1.7 °C. It is recommened that more research should be done on alternative sources of energy such as wind and solar energy to check their suitability and applicability in South Africa.

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DEDICATION

I dedicate this research to the Lord God Almighty who gave me all the knowledge and understanding that I needed to accomplish this research. If it was not for Him this work could not have been accomplished. I can do all things through Christ who strengthens me.

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LR	Linear regression
MK	Mann Kendall
NEMA	National Environmental Management Act
CO_2	Carbon dioxide
GHG	Greenhouse gas
EMS	Environmental Monitoring System
WNA	World Nuclear Association

CHAPTER ONE: INTRODUCTION

1.1. Background

The energy sector is one of the biggest sources of greenhouse gas (GHG) emissions in the world (Jauhiainen, 2008). Most of South Africa's energy supply is based on coal-generated electricity (SAEO, 2012). Energy production and consumption place considerable pressure on the environment in that they generate GHG emissions and air pollutants. They also alter land use patterns (SAEO, 2012). Energy is vital for human livelihood and is necessary for several aspects of society, from powering the economy, to lighting up homes, cooking and fuelling transport. However, it also contributes to global warming (SAEO, 2012). The energy industry has environmental impacts through its activities and these effects may change the environment; for example, by causing climate change (Jauhiainen, 2008). The efficiency of converting coal into electricity matters as more efficient power plants use less fuel and emit less climate-damaging carbon dioxide (CO_2) (IEA-CIAB, 2010).

Coal-fired plants, also known as power stations, provide over 42% of global electricity supply. At the same time, these plants account for over 28% of global CO_2 emissions (IEA-CIAB, 2010). Coal burning is one of the factors mainly responsible for climate change and global warming. This is because most power plants in South Africa directly depend on the burning of coal for the production of electricity. In South Africa, the most abundant source of energy is coal. As a result, Eskom relies on coal-fired power stations to produce approximately 90% of its electricity (Eskom, 2016). During the production of electricity, GHGs are emitted to the atmosphere, contributing to global warming. This affects the behaviour of climatic parameters such as the temperature, rainfall and evaporation, over a long period of time, hence causing climatic trends.

1.2. Statement of the problem

The generation of electricity through coal burning releases GHGs and is one of the major contributors or causes of global warming. Generation of electricity in South Africa is directly dependent on the use of coal and hence contributes environmental/global warming. As the demand for electricity increases so does the use of coal, and the intensity of global warming. GHGs cause global warming by depleting the ozone layer. This problem needs to be attended to, as its implications affect the environment severely, even the future. If no solution and precautions are taken, South Africa's environment will threaten the survival of both fauna and flora due to extreme temperatures. Global warming also affects behavioural patterns of the hydrological cycle.

Witbank is one of the areas with many coal power stations in South Africa. There are a total of six coal power stations in the area. In addition to coal usage for electricity, coal is also used for cooking and warming homes. The use of coal for all these purposes results in additional CO_2 emissions into the atmosphere and hence contributes to climate change in the long term.

1.3. Motivation

Due to an increasing rate of global warming, it is important to study the main factors contributing to global warming such as power generation and GHG emissions and strategies that can be implemented to reduce the warming rate. Power generation and the conservation of the environment are two aspects which are vital for human livelihood. Therefore, there is a need to research on the impacts of coal power generation on the environment.

This study shows the link between GHGs emitted from coal-power plants with climatic and hydrological trends in the study area. The study provides the information required for policy makers to develop policies for effective utilization and conservation of the environment by showing the impacts of global warming associated with GHGs on climatic and hydrological trends. Several studies have focused on detecting the trends of GHGs emissions from different sectors (DEAT, 2009), and detecting the temperature and precipitation trends (Neha, 2012). Some studies have focused on the effects of climate change on water resources, whilst others have focused on estimating emissions from coal-fired thermal power plants. Examples of such studies are Masese *et al.* (2012) and Moti (2010). However, studies that integrate the effects of coal power stations on GHGs, climate change and hydrology are scarce, especially in South Africa or have not yet been done. This makes this study to be of vital importance in South Africa.

1.4. The main objective

- The main objective of the study is to investigate the impacts of GHGs from coal power stations on climatic and hydrological trends in the Witbank area.

1.5. Specific Objectives

- To determine the GHGs emissions, climatic and hydrological trends in the study area
- To link the GHGs emissions trends to the climatic and hydrological trends
- To suggest or adopt emission control strategies

1.6. Research questions

- What type of GHGs emissions, climatic and hydrological trends exist in the study area?
- How do the GHG emissions impact on climatic and hydrological trends in the Witbank area?
- What are the emission control strategies that can be implemented?

1.7.The study area

1.7.1 Location

The study area (Figure 1.1) is located in Mpumalanga Province, South Africa. The study sites are located in Witbank, Middelburg, Orgies and Secunda areas. The study area was selected because it is one of the areas with many power stations in South Africa. Table 1.1 provides a summary of their characteristics.

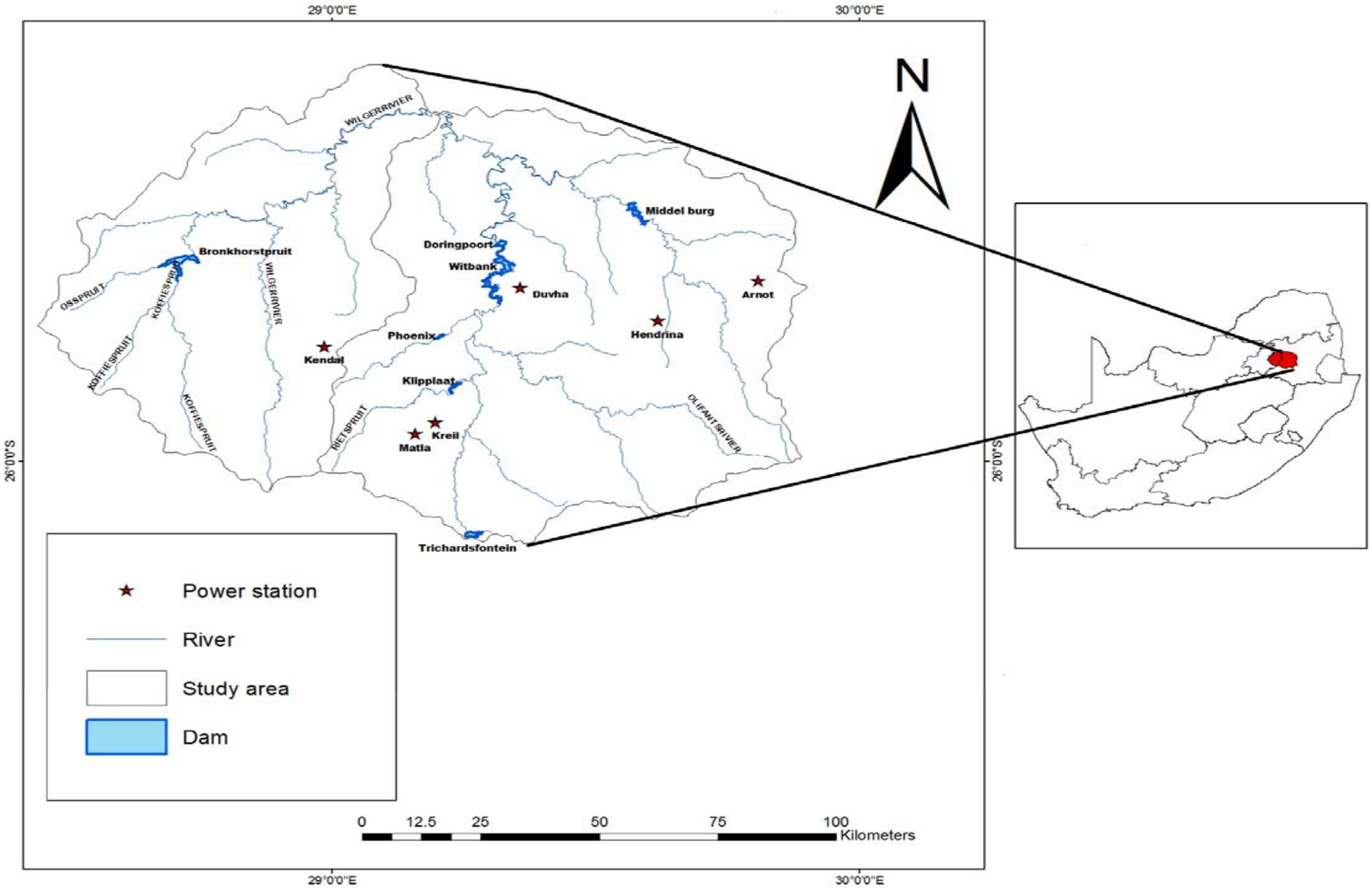


Figure1.1: Map of the study area

Table 1.1 Characteristics of the coal power stations

Power stations	Location	Year of Construction	Year of Operation
Arnot	Mpumalanga Approximately 50 km east of Middelburg	1975-1986	1975
Duvha	Located approximately 15 km east of Witbank in Mpumalanga	1975	1984
Hendrina	Approximately 40 km south of Middelburg in Mpumalanga	1970	1976
Kendal	Approximately 40 km of south west of Witbank in Mpumalanga	1982	1993
Kriel	Located between the towns of Kriel and Orgies in Mpumalanga	Construction was started in the early seventies and was completed in 1979	1979
Matla	Located approximately 30 km from Secunda in Mpumalanga	1974	1983

1.7 Climate

Climate is largely controlled by the movement of air masses associated with the Inter-Tropical Convergence Zone (ITCZ). During summer, high land temperatures produce low pressures and moisture is brought to the Olifants River Catchment, within the study area, through the inflow of maritime air masses from the Indian Ocean (Banks *et al*., 2011). During winter, the sun moves north and the land cools, causing the development of a continental high pressure system. Rainfall is therefore seasonal and occurs mainly during the summer (October to April) (Banks *et al*., 2011). The annual rainfall over the Olifants River catchment is generally between 500 and 800 mm, but exceeds 1000 mm over parts of the Highveld (McCartney *et al*., 2004). The mean annual rainfall in the Upper Olifants catchment is 689 mm, whilst the mean annual evapotranspiration rates for the catchment is 1450 mm (McCartney *et al*., 2004).

1.8 Hydrology

There are 7 dams in the study area; namely, Middelburg, Doringpoort, Witbank, Phoenix, Klipplaat, Trichardsfontein and Bronkhorstspruit. There are also a number of rivers flowing through the study area. These include the Olifants, Trichardspruit, Reitspruit, Wilgerrivier, Koffiespruit and Osspruit Rivers, amongst other non- perennial rivers (Figure 1.1).

1.9 Land use/cover

Coal power stations for electricity production occupy most of the land in the study area. The study area is mainly utilized for power production purposes, although there are other land uses, such as human settlements and dams/reservoir.

CHAPTER 2: LITERATURE REVIEW

2.1 Preamble

In this chapter literature on coal power production and its contribution to GHGs, climate change and global warming and links to water resources is reviewed. Previous studies that have been done on the impacts of coal power stations on the environment, GHG emissions and impacts of global warming on climatic trends, along with the methods used to determine climatic trends, were reviewed. Emission control strategies were also reviewed.

2.2. Greenhouse gases and their contribution to climate change

GHGs are those gases that contribute to the greenhouse effect, an overall warming of the Earth, as atmospheric gases trap electromagnetic radiation from the sun that would otherwise have been reflected back into space. Examples of such gases are methane (CH_4), nitrogen dioxide (NO_2), CO_2, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6). GHGs are naturally present in the atmosphere. GHGs (including water vapour, carbon dioxide, methane, nitrous oxide, and others) strengthen the greenhouse effect in the atmosphere, this is the so-called additional greenhouse effect (Deshmukh, 2013). This leads to an increase of global surface and atmospheric temperatures; referred to as global warming. Global warming causes different changes such as increases in extreme weather events, rising sea levels, ecosystem migrations (Deshmukh, 2013).

Climate change is a long-term continuous change to average weather conditions (Keely, 2016). It is slow and gradual, and unlike year-to-year variability, it is very difficult to perceive without scientific records (Keely, 2016). Demographic expansion and industrialisation changes in the land use patterns of ecosystems through anthropogenic activities for energy and food production has contributed to climate change. Changes in the sources and sinks of GHG, in terms of their type and their quantity, consequently cause a net increase in atmospheric GHG concentrations. A high atmospheric concentration of GHGs leads to high strength of the greenhouse effect. The high strength of the greenhouse effect leads towards global warming/climate change.

Emissions of CO_2 by human activities is currently more than 130 times more than the quantity emitted by volcanoes, amounting to about 27 billion tonnes per year (VGTE, 2007). CO_2 is the GHG that is directly affected by electricity generation, as it is emitted in high concentrations during coal burning. Coal power plants are known to release GHG emissions such as CO_2, NO and Methane (CH_4) during the process of electricity generation. These GHGs tend to heat and deplete the ozone layer that prevents ultra violet (UV) light rays from heating the earth extensively because they stay longer and are non-volatile, especially CO_2.

Moti (2012) conducted a study on estimation of emissions from coal-fired thermal power plants in India from 2001-2009. The estimated parameters were CO_2, SO_2 and NO from thermal power plants in India. The emission estimates were based on a model in which the mass emission factors are theoretically calculated using the basic principles of combustion and operating conditions. Future emission scenarios for the period of up to 2020-21 were generated based on estimates for the nine-year period. The future emission scenario, based on the projected coal consumption in India's thermal power plants, by planning commission of India under Business as usual (BAU) and Best Case Scenario (BCS), showed emissions in the range of 714976 to 914680 Gg CO_2, 4734 to 6051 Gg SO_2 and 366 to 469 Gg NO in the years 2020-21. It was stated that an increase in use efficiencies in electricity generation by thermal power plants can significantly reduce the emissions of greenhouse and polluting gases.

The University of Southern California (USC) (2016) conducted a case study which provided a detailed examination of GHG emissions from electricity consumption for 38 prominent buildings and chiller units on the University Park Campus (UPC) and the Health Sciences Campus (HSC) between 2001 and 2009. The buildings were organised into three groupings: residence halls, classrooms and academic halls, and others. These groupings were selected to better illustrate the differences in emissions between buildings that serve similar functions and to cross-compare buildings whose functions and usage patterns vary. Examining building performance at the annual, monthly and daily time scales gave some insight into a number of trends and drivers of energy consumption, including seasonal variation, usage patterns, building types and functions, daily load requirements and peak demand. More than 70% of USC'S GHG emissions between 2001 and 2009 were a result of electricity consumption. During this period, electricity consumption grew by 37%, however CO_2 emissions from electricity only grew by 16%.

DEAT (2009) conducted a study on detecting the trends of GHG emissions according to sectors for the years 1990, 1994 and 2000 in South Africa. The research was carried out using the greenhouse inventory method. The study showed the contributions of individual sectors as well as changes to the total GHG emissions for the years 1990, 1994 and 2000. The emissions of GHGs, calculated as CO_2-equivalent emissions, were up by more than 25% in 2000 compared to the base year of 1990. Against 1994 levels, this represented an increase of 14.8% (DEAT, 2009). Agriculture and waste sectors showed a significant decrease of emissions from 1990, whereas industrial processes and other product use emissions showed an increase of above 100% from 1990 to 2000 (DEAT, 2009). Energy sector emissions showed an increasing trend from 1990 to 2000, although the increase from 1994 to 2000 was half that from 1990 to 1994 (DEAT, 2009). The general trend is one of increasing emissions for all types of GHGs, without any decreases. Methane showed the highest increase, of more than 76% while nitrous oxide showed the lowest increase of 2.7% (DEAT, 2009).

Pretorius *et al*. (2015) investigated historical and projected future trends of GHG emissions which included total primary particulate matter (PM), sulphur dioxide (SO_2) and nitrogen oxides (NOx) and CO_2) in South African coal-fired power station. Historical emissions and energy production information for Eskom power plants over the period 1999 to 2012 were obtained from the Eskom energy utility's annual reports. Total annual PM emissions in these reports were estimated by means of continuous opacity monitoring systems and estimated volumetric flow rates of flue gas in power station stacks. NOx, SO_2 and CO_2 annual emissions were estimated from mass-balance equations and annual coal consumption tonnages. Relative emissions from coal fired power stations were calculated by normalizing the absolute emissions (in units of mass per annum) for total electricity production per annum. Projections of future coal fired power station criteria and CO_2 emissions were made for four different future scenarios for the period 2015 to 2030. It was found that an energy restricted environment has an increasing effect on emissions, as emissions per energy unit increased from the onset of the South African energy crisis. The study concluded that it seemed unlikely that the South African climate commitment target for 2030 will be met. This study by Pretorius *et al*. (2015) relates to the current study as historical emissions and energy production information for Eskom power plants over were obtained from the Eskom energy utility's annual reports.

2.3. Climate change detections and impacts on water resources

Climate change detection requires long records of observed data for climate elements that have the potential to show large climate change signals relative to natural variability. It is also necessary that the observing system has sufficient coverage so that the main features of natural variability and climate change can be identified and monitored (Mitchell et al., 2001). It also involves observational records and climate projections which provide abundant evidence that water resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems (Bates et al., 2008).

Climate change is having a multitude of immediate and long-term impacts on water resources in African countries. These include flooding, drought, sea-level rise in estuaries, drying up of rivers, poor water quality in surface and groundwater systems, precipitation and water vapour pattern distortions, and snow and land ice mal-distribution (Urama and Ozor, 2010). Countries in sub-Saharan Africa are likely to suffer the most devastating impacts of climate change because of their geographical location, low incomes, low technological and institutional capacity to adapt to rapid changes in the environment, as well as their greater reliance on climate-sensitive renewable natural resources sectors such as water and agriculture (Eboh, 2009). African countries are particularly susceptible to climate change due to the desertification process, declining run-off from water catchments, declining soil fertility, dependency on subsistence agriculture, the prevalence of AIDS and vector-borne diseases, inadequate government mechanisms and rapid population growth (Anyadike, 2009).

Worldwide, climate-related warming of oceans, lakes and rivers has been observed over recent decades, with implications for freshwater ecosystems, such as changes in water salinity, water nutrient content, concentration of pesticides and other pollutants, salinization of groundwater, water chemistry and pH balance (Bates et al, 2008; Sommaruga-Wograth et al., 1997; Rogora et al., 2003; Psenner and Schmidt, 1992). Generally South Africa has an arid to semi-arid climate of which less than 9% of annual rainfall ends up in rivers, and only about 5% recharges groundwater in aquifers (SANBI, DEA and GIZ, 2013). Climate change impacts on water in South Africa could exacerbate existing water-related challenges and create new ones related to climate variability, extreme weather events and changing rainfall seasonality (SANBI, DEA and GIZ, 2013).

Neha (2012) conducted a study on detection of trends in annual temperature and precipitation using Mann Kendall (MK) test to assess climate change on selected states of the North-eastern United States. The MK test was run at 5% significance level on time series data for each of the nine states for the time period, 1900-2011. For temperature, all the states indicated statistically increasing trends, except for Pennsylvania and Maine which did not indicate statistically significant trends. In the case of precipitation, the states of New Hampshire and Maine did not show statistically significant results, while other states showed statistical increasing trends.

Chattopadhyay and Edwards (2016) researched on long-term trends in precipitation and air temperature for Kentucky in United States. Non-parametric statistical tests were applied to homogenized and (as needed) pre-whitened annual series of precipitation and mean air temperature during 1950–2010. Significant trends in annual precipitation were detected (both positive, averaging 4.1 mm/year) for only two of the 60 precipitation-homogenous weather stations (Calloway and Carlisle counties in rural western Kentucky). Only three of the 42 temperature-homogenous stations demonstrated trends (all positive, averaging 0.01 °C/year) in mean annual temperature.

Azadani (2012) modelled the impact of climate change on water resources using Water Evaluation and Planning (WEAP) software to provide results for the water managers and policy makers at Arkansas River Basin in Colorado. Two climate scenarios (A2 and B2) and a 550 ppm policy were used to project future temperature and precipitation in the Arkansas River Basin for the period of 2013 to 2040. Based on the results from the two climate scenarios, a warmer and drier climate was anticipated for the region. Three adaptation scenarios (new irrigation technology, irrigation technology along with crop change, and irrigation technology along with reducing crop area) were analysed to consider their effects to mitigate the negative impact of climate change on the Arkansas River Basin. The results of the simulation of these scenarios showed that all three have a relatively short term impact, indicating that global warming is a potentially serious problem for water management in the Arkansas River Basin.

Chirima *et al.* (2012) used Cumulative Sum (CUSUM) and Exponentially Weighted Moving Average (EWMA) control charting techniques to determine if the climate of Masvingo station in Zimbabwe has changed over the past years. The climate indicator considered in this study was the annual air temperatures for Masvingo station for the period 1952 to 2001. Two control charts were applied to the data and both techniques proved to be effective in detecting climate change. However, the CUSUM chart detected a significant shift in the mean annual air temperatures in 1983, while the EWMA chart detected the shift in 1993. The two methods suggested that the origin of the shift was in 1981. The use of the two techniques confirmed the existence of climate change in Masvingo, Zimbabwe and that temperatures are getting warmer yearly.

Young (2003) researched on the effect of climate change and variability on streamflow in South-West Western Australia. This was achieved by examining the relationship between rainfall and streamflow and by providing further insights into the processes of runoff due to change in climate through hydrological modelling. The effect of natural climate variability and declining rainfall was captured using a stochastic model of rainfall time series, which produced rainfall simulations over the next 100 years. Subsequently, the impact of the rainfall simulations on streamflow response was examined using the lumped conceptual hydrological model, Large Scale Catchment Model (LASCAM). The rainfall-runoff relationship was interpreted as strongly non-linear and dominated by a threshold limit. Substantial decreases in runoff were observed in response to moderate decreases in the simulated rainfall. The main controls governing runoff production were shown to include both meteorological and hydrological factors (antecedent soil moisture capacity, interception losses and evapotranspiration processes).

Department of Water (2009) researched on streamflow trends in South-West Western Australia to determine whether streamflow records exhibited evidence of change either gradually (trend) or abruptly (step-change). Streamflow characteristics were analysed for the period of record post 1975 at 29 sites across South-West Western Australia. The finding of the study included the following: some sites showed additional step-change, but a consistent regional reduction in streamflow similar to the step-change observed in 1975 in South-West Western Australia was not observed. The majority of sites showed a negative trend indicating a decrease in streamflow, yet very few of these were statistically significant. The study suggested that interpretation of the data for possible causes of streamflow change were needed at the local study level using its findings as a reference.

Dagada (2013) used MK and linear regression (LR) methods to determine climate change and evaporation trends. Landsat maps were used to determine the land use changes of the Luvuvhu River in South Africa. The study investigated the long-term changes in evaporation and links to climate change and land use. Statistical and trend analyses methods were used to determine changes in evaporation, establishing a link between land use and evaporation changes. The results from MK and LR showed increasing trends in maximum and minimum temperatures and evaporation for all the stations. The study concluded that changes in the evaporation rate were caused by an increase in temperature and land use changes. In addition, variations in land use activities were found to be the cause of the spatial variation in evaporation rate (Dagada, 2013).

2.4. Strategies to reduce CO_2 emissions from coal power plant

Osman *et al.* (2014) reviewed Carbon dioxide Capture and Storage (CCS) with relevance to the South African power sector. These CCS methods are discussed following Osman *et al.* (2014).

2.4.1 Gas absorption using solvents

CO_2 is absorbed by passing the flue gas through an absorber through which solvent flows counter-currently. CO_2 is selectively absorbed into the solvent and exits through the bottom, while other flue gas components are passed out through the top of the absorber. The solvent loaded with CO_2 is then heated and sent to a stripping column where desorption occurs. CO_2 is released, while the unloaded solvent is recycled to the absorber. Pilot plants for processes of this type have already been set up in Austria and the Netherlands in 2008 (Knudsen *et al*. 2008; VSN, 2011).

The advantage of this strategy is that the process is well developed as it is already in use for other gas treatment requirements such as desulphurisation and denitrification processes. There are many possible solvents and solvent mixtures that are under investigation for CO_2 absorption, including amine and carbonate solvents, as well as ionic liquids. However, this process requires more energy. Hence, CO_2 absorption increases with decreasing temperature, requiring flue gas to be cooled for CO_2 absorption, as flue gas is available at a relatively high temperature of up to 413 K (Osman, 2010), thereafter, the loaded solvent needs to be heated in the stripping column to release CO_2 and recycle the solvent.

2.4.2 CO_2 capture using dry regenerable sorbents

Flue gas is first cooled and then sent to a carbonation reactor, which is a packed or fluidised sorbent bed reactor. CO_2 is absorbed or adsorbed into the sorbents. This process may be physical or reactive. The sorbent, now loaded with CO_2, is then transferred to a regenerator where it is heated to release the CO_2. The sorbent is then recycled to the carbonation reactor (Osman, 2010). Details of a pilot plant set-up and usage are provided by Manovic *et al.* (2008) who utilised a fixed bed reactor. Fluidised bed pilot projects have also been considered in Canada and Korea Yi *et al.* (2007) and Lu (2008).

The advantage of this method is that CO_2 capture is efficient even at low CO_2 concentrations in the flue gas. Depending on the sorbent and process design, lower regeneration energy requirements can be achieved than those from absorption using amine solvents (Lentech Water Treatment Solutions, 2009; VSN, 2011).

However, the low attrition resistance of many sorbents is a fundamental setback to their implementation as a CO_2 capture technique (Figueroa *et al.*, 2008; Knudsen *et al.*, 2008). While single-cycle results seem promising, many sorbents are not robust enough to be used in multi-cycle operation with conventional solids handling techniques. Sorbent pellets may erode or become caked and lose shape. High water content in the flue gas results in further attrition and sorbent caking. Moreover, the expensive nature of solids handling, including conveyor belts and compressed air blast loops which require maintenance, also reduces the feasibility of using sorbents as a CO_2 capture technique.

2.4.3 Membrane separation

Flue gas enters into a membrane separation unit. CO_2 selectively permeates through the membrane while other flue gas components do not. Flue gas passes out as stack gas, while CO_2 is recovered and compressed on the other side of the membrane. While membranes can be used on their own, increased efficiency is noted when solvents are used as a sweep fluid to accelerate mass transfer and recover CO_2 on the other side of the membrane. Some solvents, such as ionic liquids, are combined into the membrane pores to increase CO_2 permeability through the membrane (Figueroa *et al*., 2008). Common membrane material includes zeolite, ceramic, polymer and silica. More fragile membranes are supported by alumina to increase their robustness. Depending on the type of filtration unit, the process can operate in batch or continuous mode. A pilot plant in the Netherlands which accommodates CO_2 capture using membranes combined with solvents was constructed in 2008 (Knudsen *et al.,* 2008).

The advantage of membranes is that CO_2 can potentially be recovered at high purity. Membrane units are well developed and there is high scope of study regarding membrane types and solvent combinations. If no solvent is used, then solvent regeneration and recycling is not required. The challenge in implementing membrane separation for CO_2 capture is the high pressure that the process demands. The flue gas needs to be compressed before undergoing filtration in order to achieve a high CO_2 removal rate, which amounts to a high energy penalty. Moreover, many types of membrane material cannot satisfy optimum CO_2 permeability and selectivity constraints and are not robust enough for long-term operation.

2.4.4 Enzyme-based systems

Flue gas passes through the liquid membrane. CO_2 is hydrated and permeates as carbonic acid (HCO3-) at a faster rate than N_2, O_2 and other flue gas components. CO_2 is recovered under pressure or using a sweep gas on the other side (Figueroa *et al*., 2008). A popular enzyme for CO_2 capture is carbonic anhydrase. CO_2 recovery with this technique can potentially be as high as 90% (Figueroa *et al*., 2008). About 600 000 molecules of CO_2 are hydrated by one molecule of carbonic anhydrase (Ge *et al.,* 2011) A further advantage is that the heat of absorption of CO_2 into carbonic anhydrase is comparatively low. Instead of using conventional membranes as enzymes can be used as a liquid membrane suspended between hollow fibre supports for rigidity. Another advantage is that regeneration energy required is lower than that for conventional sorbents and solvents (Figueroa *et al*., 2008).

Disadvantages include limitations at the membrane boundary layers, long-term uncertainty, and sulphur sensitivity of the enzyme (Trachtenberg *et al*., 1999). This prompts ongoing research on new enzymes. Research in this technique has not gone beyond laboratory studies on CO_2 permeability and selectivity (Trachtenberg *et al*., 1999; Ge *et al.,* 2011). Metal organic frameworks (MOFs) are hybrid organic/inorganic structures containing metal ions geometrically coordinated and bridged with organic bridging ligands (Plasynski *et al*., 2011). This arrangement increases the surface area for adsorption, enabling them to be used as sorbents or as nanoporous membranes. MOFs possess much potential for CO_2 capture because there are hundreds of possible MOFs that can be developed using various combinations of metal ions and organic ligands. They can be tailor-made to suit a particular application such as CO_2 capture (Trachtenberg *et al.,* 1999). MOFs containing zinc and magnesium ions provide higher CO_2 adsorption and are hence being thoroughly investigated (Yazaydın *et al*., 2009; Simmons *et al*., 2011). The study of MOFs is still in its infancy, with investigations being made primarily on a laboratory scale.

2.4.5 CO_2 enhanced coal bed methane recovery

Enhanced coal bed methane (ECBM) recovery involves the extraction of methane gas from coal seams using CO_2. The process of extraction is similar to enhanced gas recovery but is done with coal seams. CO_2 is injected into an un-minable or unfeasibly minable coal bed and methane is forced up through a drilled outlet channel. Conventional extraction techniques recover 50% of methane in coal beds. The use of CO_2 in ECBM has the potential to increase methane recovery to 90% or even 100% (IEA, 2009). While the strategy seems theoretically attractive in terms of methane recovery, the main concern with ECBM recovery is the potential for CO_2 leakage which might occur as a result of the relatively shallow depth of extraction and the permeability of coal seams that are required. Although shallow depth and permeable rock facilitate efficient methane recovery, they also are conducive to permanent, stable CO_2 storage. Moreover, for leakage to be prevented and for predictable channelling of methane and CO_2 to occur, the coal bed has to be sufficiently thick, which requires an amount of coal to be left un-mined and the mine must be rendered un-minable. A thorough feasibility analysis is required to ensure that ECBM is worth the cost of un-mined coal. Additionally, coal mines that seem uneconomical to mine presently may be economically minable with technological development in the future. However, CO_2 ECBM may render these coal mines permanently un-minable.

ECBM operations are currently underway in Canada, China, Japan and Poland (IPCC, 2005). The strategy has some potential in South Africa because of the vast number of coal beds in the country. However, coal beds offer the least amount of storage potential in South Africa and worldwide because of their shallow depth and capacity compared to other types of potential storage reservoirs, and the permanent loss of currently un-minable coal.

2.4.6 Oxy-fuel combustion

This technique is a modification of the PC power plant. It involves burning coal in nearly pure oxygen. Oxygen is cryogenically separated from air in an air separation unit. Other air components are emitted into the atmosphere while oxygen is used in the boiler for coal combustion. The resulting heat converts water to superheated steam, for use in steam turbines. The resulting flue gas from combustion is treated for ash and sulphur removal, and thereafter contains CO_2 and water vapour. Water is separated from CO_2 by cooling the flue gas.

The main advantage of the process is that the flue gas is available at a high CO_2 concentration of approximately 75.7 mol% (Davison, 2007), thereby reducing compression costs and facilitating efficient CO_2 removal (Davison, 2007). Moreover, CO_2 is easily separated from H_2O. The modification of PC to oxy-fuel combustion is also easier than constructing an IGCC process. Oxy-fuel combustion is estimated to inherently result in lower CO_2 emissions than IGCC and conventional PC processes (Davison, 2007).

The disadvantage is the high flaming temperature at which coal burns in the presence of pure oxygen, which puts much strain on the material of construction (Arshad, 2009). To mitigate this, flue gas is recycled to enable temperature control. Captured and cooled CO_2 streams may also assist in lowering the temperature of the boiler. Moreover, air separation units require high amounts of energy to obtain pure oxygen from air. Cryogenic methods are also presently accompanied by high energy penalties.

2.5 Alternative strategies for reducing GHG emissions from coal power stations

Below are alternative methods that could be used to generate electricity with much less or no emissions of GHGs. These methods can be considered and be used for power generation, provided the conditions for implementing such methods are suitable. Looking into these methods as alternative methods is important as they could replace coal power generation and emit less GHGs, as well as reduce the demand for coal for power generations.

2.5.1 Hydropower

Hydropower is generated from the energy of falling water or running water, which may be harnessed for useful purposes. Hydropower is fuelled by water therefore, it is a clean fuel source. It does not pollute the air like power plants that burn fossil fuels, such as coal or natural gas. In addition, water is a renewable resource; therefore, hydropower is a renewable power source as it is highly dependent on water. Most hydropower installations are required to provide some public access to a reservoir to allow the public to take advantage of these opportunities. Other benefits may include water supply and flood control. South Africa can also benefit from macro-hydro by importing from its neighbouring countries that have a huge hydropower development potential, from pumped storage, and from dams/transfers (Musango *et al.*, 2011).

Smit (2011) stated that hydropower can impact on water quality, flow and can cause low dissolved oxygen levels in the water, a problem that is harmful to riparian (riverbank) habitats. The major disadvantage of hydropower is that when water is not available in ample quantity, the power plants cannot produce electricity and that they can be impacted by drought. For South Africa, this source of energy is not reliable as an alternative source due to the fact that South Africa does not have that many large rivers. The construction of a hydropower facility, with dams and water transfer schemes, will therefore have a significant impact on the receiving environment. The cost associated with constructing such a facility also has an impact on its feasibility, especially in a country with limited resources and sites to develop hydropower facilities (Smit, 2011).

2.4.2 Wind energy

Wind power is a clean and renewable energy resource that has no risk of fuel price variation. Therefore, wind power is an important power type for sustainable development (Wang and Chen, 2009). Wind energy, other than being clean and renewable, is relatively cheap. Its advantages are largely global in nature (For example, reduced GHG emissions, reduced damage to the environment and fossil fuel depletion), and the disadvantages are primarily local (for example, land use, noise and visual pollution). The main disadvantage of wind power is that the wind does not blow consistently or steadily. South Africa has a very long coastline with strong winds. Unfortunately, the areas that are most suitable for the development of wind energy overlap with prime tourism areas, like the West Coast. In order for wind energy facilities to be economically viable, several units need to be placed together in a wind farm development. These farms have a significant visual impact on the surrounding area. Although wind energy is regarded as a form of green energy, the footprint of a wind farm, which entails the construction of terraces for the wind turbines, is a matter of concern to the agricultural sector, as it represents a substantial loss of agricultural land (Smit, 2011). In South Africa, there is the potential for electricity generation from wind energy along the coastal areas (Asamoah, 2003; Sebitosi and Pillay, 2008), particularly in the Western Cape Province and parts of the Eastern Cape Province, and the Northern Cape Provinces (Hagemann, 2008). According to Szewczuk and Prinsloo (2010), several studies provide estimates of the wind energy potential in South Africa and range from a low of 500 MW to a high of 56000 MW (Musango *et al*., 2011).

2.4.3 Solar energy

Solar energy refers to sources of energy that can be directly attributed to the light of the sun or the heat that sunlight generates (Bradford, 2006). Solar energy is free, although there is a cost in the building of ‘collectors’ and other equipment required to convert solar energy into electricity or hot water. It is used in remote areas where it is too expensive to extend the electricity power grid. Solar energy is infinite. Timilsina *et al.* (2012) stated that solar energy constitutes the most abundant renewable energy resource available and, in most regions of the world, its theoretical potential is far in excess of the current total primary energy supply in those regions. In South Africa, there is an enormous potential for the development of solar energy since the country has 24% of the world’s best winter sunshine area (Musango *et al.,* 2011). It is also a non-polluting technology, which means that it does not release GHGs. In addition it is a noiseless technology, as there are no moving parts involved in energy generation. This technology requires low-maintenance because of lack of moving parts. It is the most viable alternative for providing electricity in remote rural areas, as it can be installed where the energy demand is high and can be expanded on a modular basis (Smit, 2011). Solar energy can also play a role in reducing the warmth of the earth as it absorbs some heat and transfers it to power. Solar energy technologies could help address energy access to rural and remote communities help improve long-term energy security and help greenhouse gas mitigation (Timilsina *et al*., 2012).

Solar energy is heavily dependent on atmospheric conditions; it can only be harnessed when it is daytime and sunny. Solar insolation also varies from location to location. As a result, there are certain geographic limitations in generating solar power, for example, in countries such as the UK, the unreliable climate means that solar energy is unreliable as a source of energy. This is because cloudy skies reduce its effectiveness. Solar collectors, panels and cells are relatively expensive to manufacture, although the prices are falling rapidly. Solar power is also used to charge batteries so that solar powered devices can be used at night. However, the batteries are large and heavy and need storage space. They also need replacing from time to time. The solar plant itself will cover large areas of agricultural land or natural vegetation which would have to be cleared of all large trees and buildings to ensure maximum radiation (Smit, 2011). Such a solar park would be visible over long distances and would impact negatively on several other economic sectors, such as tourism, agriculture and conservation (Smit, 2011).

2.4.4 Comparison of energy sources

The use of coal energy means that the forest and soil will be damaged. The development of petroleum projects in the sea will also affect the environment of the sea and the hydropower station will harm the live environment of fish. Compared with other power plants, wind power is simple and easy. Hydroelectric power plants need to consider some complex problems, such as silting, and resettlement (Wang and Chen, 2009). The WNA (2011) reported on comparison of lifecycle GHG emissions of various electricity generation sources, namely: nuclear, coal, natural, gas, oil, solar photovoltaic, biomass, hydroelectric and wind. Coal-fired power plants have the highest GHG emission intensities on a lifecycle basis. Although natural gas, and to some degree oil, has noticeably lower GHG emissions, biomass, nuclear, hydroelectric, wind and solar photovoltaic, all have lifecycle GHG emission intensities that are significantly lower than fossil fuel-based generation.

All the power production types have environmental effects as well as strengths and weaknesses. Although each change comes with a price, the right track in minimising the environmental impacts and assuring energy supply security is by combining all possible low-carbon technologies and by improving energy efficiency in all sectors, for creating a new power production infrastructure of tolerable energy price and of minor environmental effects (Jauhiainen, 2008)

2.4.5 Adoption of the Kyoto protocol

The Kyoto protocol is an international agreement linked to the United Nations frame work convention on climate change, which commits its parties by setting internationally binding emission reduction targets. The Kyoto protocol is a protocol to the United Nations Framework Convention on Climate Change (UNFCCC) adopted on 11 December 1997 in Kyoto, Japan and it came into force on 16 February 2005, to reduce GHG emissions. Furthermore, the UNFCCC is an international environmental agreement whose goal is to achieve stabilization of GHGs concentrations in the atmosphere at levels that would prevent dangerous anthropogenic intrusion with the climate system. The Kyoto protocol is effective towards the reduction of greenhouse gas emissions but at a small scale. Nordhaus (2005) stated that even if the current protocol is extended, models indicate that it will have little impact on global temperature change. South Africa, as a developing country, is not required to reduce its emissions of greenhouse gases. However, the South African economy is highly dependent on fossil fuels and the country can be judged to be a significant emitter due to the relatively high values that can be derived for emissions intensity and emissions per capita DEAT (2004). DEAT (2004) also stated that emissions can still be expected to increase with economic development, albeit at a smaller pace than would have happened without intervention.

2.5 GHGs detection methods

2.5.1 GHG inventory method

An inventory method is a database that lists, by source, the amount of air pollutants discharged into the atmosphere of a community during a given time period (Texas Southern University, 2012). The inventory method does not estimate GHG emissions by measuring them, but by calculating them from the fossil fuels used and from other relevant processes relating to industry and agriculture. To do this accurately requires detailed information and data from a wide range of source sectors and activities. Such an approach is based on economic activity data that complies with Inter-Governmental Panel on Climate Change (IPCC) guidelines. This method was used by DEAT (2009) and USAID (2013). It helps countries to identify their GHG emissions as per sector. This can help in reducing their emissions and also in pin pointing which sector emits more, thus they can come up with a way of reducing such emissions from that sector. The emission figures are heavily dependent on the data provided/input. Therefore, one needs to be careful when calculating the figures involved. It is difficult to estimate GHG emissions of a particular area using this method (for example, Witbank area), as its calculations are made at a large scale area (for example, that of a country). It is also not easy to estimate the emission of a single point source, as it only provides emission factors of various sectors.

The calculation of GHG emissions from a source generally involves two main components: activity data and GHG-specific emissions factors. A key exception to this description is if direct measurements, such as continuous emissions monitoring systems (CEMS), are used to quantify emissions directly without the use of either activity data or emissions factors (such as from a smokestack, in the power generation sector) (USAID, 2013).

The emission calculation for each GHG is represented by the general equation from IPCC (2006) guideline:

$$\text{GHG Emissions} = AD \times EF \qquad (2.1)$$

AD is activity data and EF is emission factor.

Activity data is defined as the magnitude of activity resulting in emissions or removals occurring during a given period of time. An emission factor is the emission rate of a given GHG for a given source, relative to the unit(s) of activity. Activity rate is the rate of GHGs emitted due to different activities falling within the four activity sectors; namely, energy, industrial processes and product use (IPPU), agriculture forestry and other land use (AFOLU), and waste. The emission factor is a figure given for a particular sector according to the IPPC (2006) guideline.

2.5.2 Improved gas chromatograph

This is an improved gas line and valve driving module that is equipped with flame ionization detector (FID) and electron capture detector (ECD) capable of measuring CH_4, CO_2 and NO_2 in air sample within four minutes. This equipment has high sensitivity, resolution and precision. The linear response range of the system meets the requirement of in situ flux terrestrial ecosystems since it is easy to use, efficacious, stable and reliable for collecting data (Ying-hong *et al*., 2006). However, the cost of GC is high, and its miniaturization for portable application needs more technological breakthroughs. Therefore, GC does not quite satisfy the device and material constraints for unattended, flexible basic sensors (Xiao *et al*., 2012).

2.6 Detection of changes in hydrological data

2.6.1 Mann Kendall (MK) test

For any data analysis or change detection study, the methods and hypothesis tested should be chosen based on data availability (time series) (Hall, 2013). The MK trend test (Mann, 1945; Kendall, 1975) is one of the widely used non-parametric tests to detect significant trends in time series (Hamed, 2007). It is robust even for highly skewed hydro-metereological data (Cherie, 2013). This test was proven by Kendall (1975) as a special case for testing correlation between two data series (Y, X) using Kendall’s 0. For this reason, it is called the MK test and it measures whether data value (Y) tends to increase or decrease with time (T) (Cherie, 2013). Hypothesis testing is a statistical validation procedure meant to check whether the statistical hypothesis is true or not (Hall, 2013). The null hypothesis (H_o) and the alternative hypothesis (H_1) are stated as follows:

H_o: No trend exists, that is, the variation of the data is random. H_1: A trend exists that can be either positive or negative.

No assumption of normality is required but the data must not be serially correlated for the computed p value to be taken as correct. This test is also invariant (monotonic) to any power transformation (such as, square roots and logarithms) which are often made to transform highly skewed data to more normally looking distributions.

According to Cherie (2013), in order to perform the test, Kendall's S statistic is computed from (T, Y) data pairs and the procedure/equations are as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} Sgn(y_j - y_i) \text{...}(2.2)$$

$$Sgn(y_j - y_i) = \begin{cases} 1 \; if \; (y_j - y_i) > 0 \\ 0 \; if \; (y_j - y_i) = 0 \\ -1 \; if (y_j - y_i) < 0 \end{cases} \text{...}(2.3)$$

It can be simplified as: $Sg = P - M$...(2.4)

Where:

P = the number of times the Y's increase as $Y_j > Y_i$

M= the number of times the Y's decrease as $Y_j < Y_i$

for all $i = 1$,---, $n - 1$ and $j = i + 1$, ---,n. Hence, there will be $n\ (n - 1)/2$ possible comparisons to be made along the n data pairs. If Y increases as T increases,

1 = + of n (n-1)/2 then the correlation coefficient 0 =+1. If Y decreases as T increases, S = + of n $(n - 1)/2$ then the correlation coefficient $\tau = +1$. If Y decreases as T increases, S = $-$ of n $(n - 1)/2$ then the correlation coefficient $\tau = -1$. It can be shown that S is asymptotically normally distributed (Hipel and McLeod, 2005) with mean E(S) = 0 and standard deviation (=(variance$^{1/2}$) σ_s given by (Helsel and Hirsch, 2002; Helsel and Frans, 2006; Cherie, 2013).

$$\sigma_s = \sqrt{\frac{n}{18}\left[(n-1)(2n+5) - \sum_{t_i=1}^{g} t_i(t_i-1)(2t_i+5)\right]} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.5)$$

where:

σ is the number of tied groups

t_i is the number of ties of extent i.

The normality distribution of S is even guaranteed for small numbers of data points ($n < 10$) if one uses the standardised variable Z defined as:

$$Z = \begin{cases} \frac{s+1}{\sigma_S} if\ s < 0 \\ 0\ if s = 0 \\ \frac{s-1}{\sigma_S} if\ s > 0 \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.6)$$

For $n \leq 10$, given the level of significance (α) determines the critical Z directly from the table of any standard statistical book. But for $n > 10$ and with the presence of ties, since the tied values of Y_i and Y_j produce 0 instead of +1 or -1; hence ties do not contribute to either P or M.

Kendall's τ can be defined as:

$$\tau = {}^{S}/_{D} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.7)$$

Where: D is the maximum possible value of S, when all data points are monotonically increasing. When no ties exist, D is a constant, so that the statistics of S and τ are the same. The null hypothesis H₀ stated above (no trend exists) is tested through the significance of S or τ, being significantly different from zero; that is, the null hypothesis is rejected at a significant level α (significant trend exist in the time series) if the computed value

$$|Z_{\acute{s}}| > Z_{i\alpha/2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.8)$$

Where: $Z_{1-\alpha/2}$ is the value of the standard normal distribution with the probability of exceedance of $\alpha/2$. For 5% significance level, the critical $Z_{1-\alpha/2}$, value which is computed from any standard normal distribution table is 1.96.

MK is the most common method used in detection of trend in a time series, particularly environmental time series (Kundzewicz and Robson, 2000; Hipel and McLeod, 2005). The reason is that MK does not require a continuous record, and is suitable for hydrological time series with gaps (Zhang *et al.,* 2001; Dagada, 2013). It is a non-parametric test (Helsel and Hirsch, 1992) and it is rank based procedure especially suitable for non-normally distributed data, censored data, and nonlinear trends (Pellicciotti *et al.,* 2017). This technique has been widely used to test for randomness against trends in climatological time series and hydrological data analysis (Helsel and Hirsch 1992; Zhang *et al.,* 2001; Pellicciotti *et al.,* 2007; Dagada 2013). The disadvantage of MK is that it is a non-parametric test and such tests identify a trend without identifying the quantity of a trend; therefore MK requires a parametric test that will identify the magnitude of the trend. To appropriately estimate changes over time, a method of assessing trend behaviour is required.

2.6.2 Spearman rho (SR)

SR is a non-parametric statistic test used to detect trends in a time series. SR is seldom used in hydro-meteorological trend analysis because SR provides results almost identical to those provided by the MK test (Yue and Wang, 2002). The strength of such non parametric test depends upon pre – assigned significance level, magnitude of trend, sample size and the amount of variation within time series (Yue *et al.,* 2002).

According to Dagada (2013) the SR test has been applied for the detection of trends in many studies such as Gellens (2000), Kahya and Kalayci (2004) and Gadgil and Dhorde (2005). The SR test is a simple method with uniform power for linear and non-linear trends and is also commonly used to verify the absence of trends (Dahmen and Hall, 1990; Tonkaz *et al.,* 2007). Like conventional correlation coefficient the Spearman p is free to have any value in between 1 and +1.

A value of 0 indicates no relationship and values of +1 or -1 indicate a one-to-one relationship be tween the variables or ‘perfect correlation’. For Spearman, unlike the Mann Kendall, very little basis exists for choosing one over the other (Daniel, 1978).

The difference between the conventional coefficient and the Spearman’s rho is that the Spearman’s rho refers to the ranked values rather than the original measurements.

2.6.3 CUSUM

Cumulative sum (CUSUM) procedure was implemented by Wayne (2000) for performing a change-point analysis. A CUSUM control chart is one of the most popular methods used to detect a process mean shift (Jong-hyun and Hong, 2010). This method has been used in several studies such as in Mussa *et al.* (2013) and Chirima *et al.* (2012). CUSUM charts are used for performing change point analysis and detection, the change point analysis is an analysis used to determine whether a change has taken place or not (Dagada, 2013).

Procedure

According to Jong-hyun and Hong (2010) the procedure for the CUSUM is as follows:

Let X_1, X_2………X_n represent the n data points. The cumulative sums S_0, S_1…….S_n are calculated iteratively in the following three steps:

1. First calculate the average $\bar{X} = x_1 + x_2 + x_3 \ldots\ldots\ldots\ldots x_n$
2. Start the cumulative sum at zero by setting $S_0 = 0$.
3. Calculate the other cumulative sums by adding the difference between the current value and the average to the previous sum.

$$S_i = S_{i-1} + (x_i - \bar{X}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.9)$$

The cumulative sums are not the cumulative sums of the values. Rather, they are the cumulative sums of differences between the values and the average. A sudden change in the direction of the CUSUM indicates a sudden shift in the average. A period when CUSUM chart follows a relatively straight path indicates a period when the average does not change. Most of the values added to the cumulative sum will be positive and the sum will steadily increase. A segment of the CUSUM chart with an upward slope indicates a period when the values tend to be above the overall average. Likewise a segment with a downward slope indicates a period of time when the values tend to be below the overall average.

To estimate the location of the change point, define m such that:

$$|S| = \max_{i=0,\ldots n} |Si| \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.10)$$

S_m is the point noted furthest from zero in the CUSUM chart. The point m estimates the last point before the occurrence of the change point. The point m+1 estimates the first point after the change. Another estimator that can be used to estimate when the change occurred is the mean square error (MSE) estimator. The MSE (m) is defined as:

$$\text{MSE (m)} = \sum_{i=1}^{m} (x_i - \bar{x}_1)^2 + \sum_{i=m+1}^{n} (x_i - \bar{x}_2)^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.11)$$

$$\text{Where} \quad \bar{X}_1 = \frac{\sum_{i=1}^{m} x_i}{m} \text{ and } \bar{X} = \frac{\sum_{i=m+1}^{n} x_i}{n-m}$$

The MSE error estimator is based on the idea of splitting the data into two segment 1 to m and m+1 to n, estimating the average of each segment, and then seeing how well the data fits the two estimated averages. The value m that minimizes MSE (m) is the best estimator of the last point before the change. As before, the point m+1 estimates the first point after the change.

CUSUM is more powerful at detecting and characterising smaller sustained change, including detection of multiple changes. It reduces the number of false detections by controlling the change-wise error rate. It is robust to outliers and can be made even more robust by performing a change-point analysis on the ranks. The same procedure works for all types of data, including attribute data, individual values, counts, averages and standard deviations. Further, a change-point analysis can be performed on ill-behaved data, such as particle counts and complaint data, which do not follow any of the traditional control charting distribution and may contain numerous outliers. It is easier to use and interpret, especially for large data sets and when multiple changes have occurred. CUSUM his method does not detect isolated abnormal points. Change-point analysis should be supplemented with a Shewhart control chart when such points are of concern. Box and Luceno (1997) demonstrated that Shewhart control charts are optimal at detecting isolated abnormal points, while CUSUM charts are optimal at detecting shifts of the mean. If one is concerned with both types of changes, both procedures can be used to complement each other.

2.6.4 Linear regression

This method was introduced by Sir Francis Galton around 1800 (Mutan, 2004). Linear regression attempts to model the relationship between two variables by fitting a linear equation to observed data (Ekstrom and Sørensen, 2014). An experimental study of the relation between two variables is often motivated by a need to predict one from the other (Wilberforce, 2007). Linear regression analysis is a simple method for investigating and modelling the functional relationship between variables and it is used almost in all fields (such as engineering, economics, management, biological and social sciences). Regression is a statistical technique that allows decision makers not only to establish quantitative relationships among such variables but also to measure the "strength" of the relationship (Wilberforce, 2007).

The general equation for linear regression can be represented by the following equation:

$$y = mx + c \qquad (2.12)$$

Where y is the dependent variable, x the independent variable, m the slope and c the intercept.

Wilberforce (2007) explains regression as follows:

In regression analysis a mathematical equation is developed which relates an unknown variable to a known quantity of interest. The known variable (X) is called the independent (explanatory, predictor) variable, while the variable to be predicted (Y) is the dependent (or response) variable. The objective is to find the nature of the relation between X and Y from experimental data and use the relation to predict the response variable Y from the input X.

Naturally, the first step in such a study is to plot and examine the scatter diagram. If a linear relation emerges, the calculation of the numerical value of R will confirm the strength of the linear relation. Its value indicates how effectively Y can be predicted from X by fitting a straight line to the data. The coefficient of determination, or R^2, expresses the strength of the relationship between the X and Y variables. It is the proportion of the variation in the Y variable that is "explained" by the variation in the X variable. R^2 can vary from 0 to 1; values near 1 mean the Y values fall almost right on the regression line, while values near 0 mean there is very little relationship between X and Y. A line is determined by two constants: its height above the origin (intercept) and the amount that y increases whenever X is increased by the unit (slope).

$$\gamma = \beta_0 + \beta_1 x \qquad (2.13)$$

This best fit line or least square line is close to the points graphed in the scatter plot in terms of minimizing the amount of vertical distance.

The main limitations of Pearson's(r) are: the method measures only a linear association between two variables; it assumes the data are distributed normally; and the value of r is disproportionately affected by outlier (Henock, 2014) and it can fail to detect trends that are nonlinear but still monotonic (gene rally in one direction) (Wilberforce, 2007). The justification for using the method is that r can be easily calculated in Microsoft Excel (Henock, 2014). In addition, it is easy to apply to a large number of sites (Wilberforce, 2007). It is also relatively easy to understand, and the statistical software designed for its estimation is widely available. Also it is a flexible and powerful method for conducting important types of analyses (Hoffmann, 2005). This method can also be used in patching missing data and to determine the significance of the trends in a series provided there are no gaps in the data.

According to Fenton and Neil (2012) a competent researcher investigating a hypothesized relationship will set a p-value in advance of the emperial study. Typically values either 0.01-0.05 are used. If the data results in a p-value of less than that specified in advance, it enables the researcher to reject the null hypothesis and conclude that a relationship really exists.

2.7 Methods of patching data

2.7.1 Arithmetic average method

This method is applied if the average annual rainfall of the station under consideration is within 10% of the average annual rainfall at the adjoining stations. The erroneous or missing rainfall at the station under consideration is estimated as the simple average of neighbouring stations. Thus, if the estimate for the erroneous or missing rainfall at the station under consideration is P_{test} and the rainfall at M adjoining stations is $P_{base,i}$ (i = 1 to M), then:

$$P_{test} = \frac{1}{m}(P_{base1} + P_{base2} + P_{base3} + \cdots + P_{basem}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.14)$$

Usually, the averaging of three or more adjoining stations is considered to give a satisfactory estimate (Hydraulic,1999).

2.7.2 Normal ratio method

This method is preferred if the average (or normal) annual rainfall of the station under consideration differs from the average annual rainfall at the adjoining stations by more than 10%. The erroneous or missing rainfall at the station under consideration is estimated as the weighted average of the adjoining stations. The rainfall at each of the adjoining stations is weighted by the ratio of the average annual rainfall at the station under consideration and the average annual rainfall of the adjoining station. The rainfall for the erroneous or missing value at the station under consideration is estimated as:

$$P_{test} = \frac{1}{M}(\frac{N_{test}}{N_{base1}}P_{base1} + \frac{N_{test}}{N_{base2}}P_{base2} + \frac{N_{test}}{N_{base3}}P_{base3} + \cdots + \frac{N_{test}}{N_{baseM}}P_{baseM}) \ldots\ldots\ldots\ldots\ldots\ldots (2.15)$$

Where:

N_{test} = annual normal rainfall at the station under consideration.

$N_{base,i}$ = annual normal rainfall at the adjoining stations (for i = 1 to M).

A minimum of three adjoining stations must be generally used for obtaining good estimates using the normal ratio method.

2.7.3 Distance power method

The rainfall at a station is estimated as a weighted average of the observed rainfall at the neighbouring stations. The weights are equal to the reciprocal of the distance or some power of the reciprocal of the distance of the estimator stations from the estimated stations. Let D_i be the distance of the estimator station from the estimated station. If the weights are an inverse square of distance, the estimated rainfall at station A is:

$$P_i = \sum_{i=1}^{n} \left(\frac{\frac{P_i}{{D_i}^2}}{\frac{1}{{D_i}^2}} \right) \quad \text{.......}(2.16)$$

The weights continue decreasing with distance and approach zero at large distances. A major shortcoming of this method is that the orographic features and spatial distribution of the variables are not considered. The extra information, if stations are close to each other, is not properly used. The procedure for estimating the rainfall data through this technique can be illustrated through an example. If A, B, C, D are the location of the stations, the distance of each estimator station (B, C, and D) from station (A), whose data is to be estimated, is computed with the help of the coordinates using the formula:

$$D_i^2 = [\,(x - x_i)^2 + (y - y_i)^2] \quad \text{.......}(2.17)$$

where x and y are the coordinates of the station whose data is estimated and x_i and y_i are the coordinates of stations whose data are used in estimation.

2.8 Data quality checks

In climatic research it is important to have access to reliable data, which are free from artificial trends or changes. One way for checking the reliability of a climate series is to compare it with surrounding stations (Yadav, 2002). Data quality check is carried out to ensure consistency in the data, identify missing gaps, and possible errors which might have occurred during data processing. Data errors are identified through visualization and the inconsistent value is eliminated and replaced through correlation with nearby stations. Missing gaps are filled using regression analysis by correlating the gaps with the nearby stations. As non-homogeneous climate data are a poor source of information for climate research, hydrologists have often preferred to use DMA (Double Mass Analysis) to obtain information on the relative homogeneity of precipitation series (Yadav, 2002).

2.8.1 Mass Curve and Double Mass Curve

Mass and double mass curves (DMC) are very basic analysis tools. A mass curve is a plot of cumulative values against time; a double mass curve is a plot of cumulative values of one variable against the cumulation of another quantity during the same time period (Searchy and Hardison, 1960). Mass and double mass curves can be applied to numerous types of hydraulic and hydrological data. The purpose of these curves is to check the consistency of data over time and to identify changes in trends through changes in the slope (Albert, 2004).

Mass and double mass analysis (DMA) are often used to adjust precipitation records. The theory behind double mass curves is that by plotting the cumulation of two quantities the data will plot as a straight line, and the slope of this line will represent the constant of proportionality between the two quantities (Albert, 2004). If the DMC does not have any breaks in slope, it means that the correlation between the two plotted values has not been changed or affected significantly over the years. However, slope breaks are common in DMCs and help provide added information about the relationship between the two variables (Albert, 2004).

Precipitation data can be very inconsistent due to non-representative factors, such as change in location or exposure of the rain gauge (Chow, 1964). Breaks in slopes within curves on the plots can be caused my many factors. These include a change in flow magnitudes, construction, urbanization, increase/decrease in vegetation, climate changes, and anything else that can effect sediment influx and discharge into a data collecting gage (Albert, 2004). The most significant information that a break in slope provides is an estimate of the time at which a change occurred (Searchy and Hardison, 1960). It is a general rule to ignore breaks in slope that persist for less than 5 years. If a break continues for more than five years, it is considered a trend and should be investigated further (Searchy and Hardison, 1960).

Step taken in checking the consistency of data using double mass-analysis

Identifying erroneous data

Compute cumulative hydrologic/rainfall amounts for suspect gauge and check gauges. Compute the mean of the annual rainfall totals measured by the check gauges. Compute the cumulative rainfall amounts for the check gauges. Plot cumulative rainfall/hydrologic data for the suspect gauge on the y-axis versus cumulative rainfall/hydrologic data for the check gauges. If the data shows that there are no errors that occurred for the suspect gauge, all points will fall (approximately) on a straight line. Divergence from a straight line indicates an error in the data for the suspect gauge; if an error has occurred, data can be corrected.

Correcting the erroneous data

Calculate the gradient of the best-fit line for the period for which no data errors are present. Calculate the gradient of the best-fit line for the period for which an error is present. Compute a correction factor k = gradient before fault/gradient after fault.

The correction factor is then applied to the erroneous data

It is applied if required, the analysis can be repeated for the corrected data to confirm that the procedure has worked satisfactory.

CHAPTER 3: METHODOLOGY

3.1 Preamble

This chapter describes methods that were used to obtain GHG data and determine GHG emission trends. It also describes the methods used to obtain climatic data as well as determining the trends in climate change and their significance.

3.2 GHGs emission acquisition

CO_2 emissions data for the six (6) power stations (Arnot, Duvha, Hendrina, Kendal, Kriel, and Matla) in Witbank was acquired from the Eskom's sustainability report/annual report. Eskom estimates its annual CO_2 emissions from mass-balance equations and annual coal consumption tonnages (Pretorius et al., 2015). GHGs emissions data was only available for the years in which monitoring was conducted. This ranged from April 2011- March 2014.

3.3 Determination of climatic and hydrological trends

Temperature data which covered the period 1950-2016 was obtained from the South African Weather Services (SAWS) and Water Research Commission (WRC) temperature database. Rainfall data was obtained from the Lynch (2004) rainfall database and SAWS. Rainfall data covered the period 1925-2016. The 91 years rainfall data was chosen because it allows enough time to analyse the hydrological and climatic trends both before and after the establishment of the coal power stations and 66 years was the number of years of available temperature data. The study analysed if there are changes in the hydrological and climatic trends that could have been caused by GHGs emissions from coal power stations. Figure 3.1 shows the stations which were used in the study while Table 3.1 shows their details. Station 05153208 had limited data which covered the period 1993-2016. Data for this station was extended using data from Lynch (2004) database to cover the period 1925-2016 so that it can correspond with the period before and after coal power stations were commissioned in order to detect trends. Scatter plots for station 05153208 versus the surrounding stations (0515412W, 0515382AW, 0515383W, 0331275W, 0442046W) were plotted and their relationships were determined using LR. The stations with highest R^2 value was used for extending data for station 05153208 since it was expected that high R^2 show high correlation of rainfall behaviour in the two stations. Homogeneity and consistency of the rainfall data used in these analyses was tested using DMA as a data quality control measure. LR was also used to patch/extend the missing data for station 05153208 temperature and rainfall data in the period 1993-2016. Annexure A shows the GPS coordinates of all the selected stations within the study area.

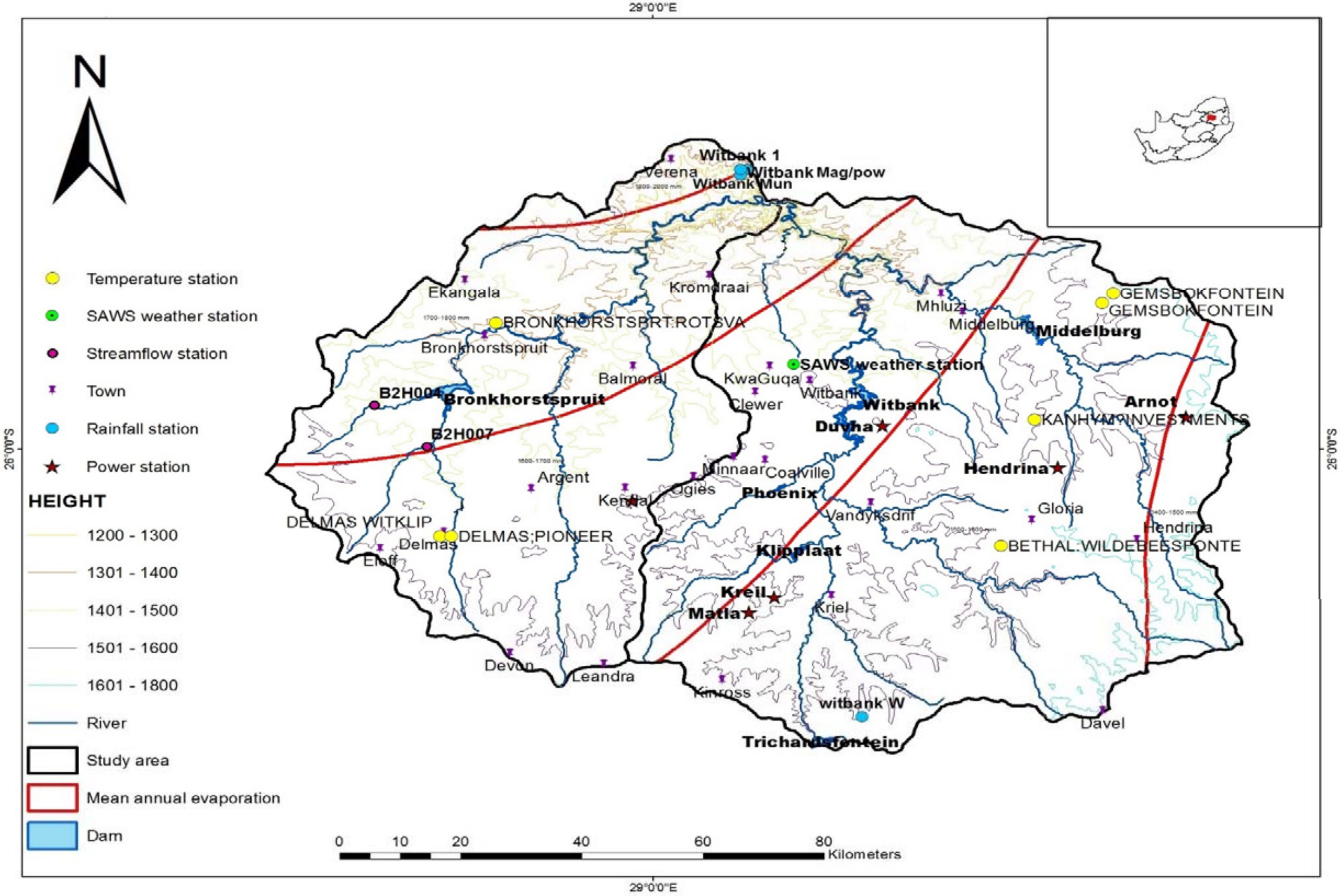


Figure 3.1. Map of all stations within the study area

Table 3.1. Details of stations used in the study area

Station name	**Station type**	**Source**	**Data length**	**Period with gaps**
SAWS 05153208	Temperature and Rainfall	SAWS	66 (1950-2016)- temperature 91 (1925-2016)- rainfall	15 months 83 months
Delmas pioneer 0477368_A	Temperature	WRC temperature database	1950-2000 (50 years)	None
Delmas witklip 0477309_AW	Temperature	WRC temperature database	1950-2000 (50 years)	None
Delmas Sensako 0477276_A	Temperature	WRC temperature database	1950-2000 (50 years)	None
Bronkhors Stprt: Rotsva 0514467_A	Temperature	WRC temperature database	1950-2000 (50 years)	None
Kanhyms-Investments 0516117_A	Temperature	WRC temperature database	1950-2000 (50 years)	None
Gemsbkfontein 0516285_W	Temperature	WRC temperature database	1950-2000 (50 years)	None
Gemsbkfontein 0516285_A	Temperature	WRC temperature database	1950-2000 (50 years)	None
Bethalwildebeesfontein 0479010_A	Temperature	WRC temperature database	1950-2000 (50 years)	None
Witbank Mun 0515412W	Rainfall	Lynch (2004)	(Nov 1993- Dec 2000) (7 years)	None
Witbank k1 0515382AW	Rainfall	Lynch (2004)	Nov 1993- Dec 2000) (7 years)	None
Witbank Mag/Pow 0515383W	Rainfall	Lynch (2004)	(Nov 1993- Dec 2000) (7 years)	None
Witbank Fontein 0331275W	Rainfall	Lynch (2004)	Nov 1993- Dec 2000 (7 years)	None
Witbank W 0442046W	Rainfall	Lynch (2004)	Nov 1993- Dec 2000 (7 years)	None
Koffiespruit@Waaikraal B2H007	Streamflow	DWS	1985-2011 (26 years)	7 months
Ossp@Boschkop B2H004	Streamflow	DWS	1985-2015 (30 years)	Year 1993

MK and LR methods were used to detect the strength and magnitude of the trends. For LR, two climatic parameters were used (rainfall and temperature). The data was organised according to hydrological year (October – September of the following year). LR method was chosen because it is a simple method for investigating and modelling the functional relationship between variables, it is used in almost all fields and determines the significance of trends. The MK method was chosen because it is the most commonly used method in detection of trend in a time series particularly environmental time series (Kundzewicz and Robson, 2000; Hipel and McLeod, 2005). The reason is that MK does not require a continuous record, and is suitable for hydrological time series with gaps (Zhang *et al*., 2001; Dagada, 2013). It has also been widely used to test for randomness against trend in climatological time series (Zhang *et al*., 2001). MK and LR trends for all the stations were detected using monthly (rainfall, streamflow and temperature) data. It was only station 05153208 whose data was analysed at monthly, seasonal and annual scales to allow comparisons with GHGs emission data since this station had extended data up to 2016. Streamflow data from streamflow stations B2H004 and B2H007 were used in order to determine the streamflow trends in various time scales of the year and to link the streamflow trends with the temperature and rainfall of the study area. Streamflow data for stations B2H004 and B2H007 for 30 (1985-2015) and 26 (1985-2011) years were obtained from the Department of Water and Sanitation (DWS). The years 1985-2015 and 1985-2011 were the only ones with available data for the B2H004 and B2H007 streamflow gauging stations, respectively. These streamflow stations were chosen because they were the ones having more data to analyse for long term LR and MK trends in the study area as compared to other stations. LR and MK methods were used to analyse the trends in streamflow. However some trends could not be detected because of lack of data within the study area which seemed impossible to patch, hence the streamflow data was not patched. This aided in detecting how climate change through temperature variations affects streamflow. The linear regression method was chosen because it is easy to use and understand; it is also cheap, widely used and reliable. For example, it was used/implemented in studies by Sunil (2011) and Hatcher (2011) to detect streamflow trends.

The significance of the trends was tested following Hall (2013) and Wilberforce (2007) by comparing the ZS (normalised MK statistic) with the computed probability. If ZS is negative, a trend was classified as decreasing and if the calculated probability was less than the significance level α, the trend was classified as decreasing significantly. A trend was said to be statistically significant increasing (positive) if the ZS was positive and the computed probability was less than the level of significance. In both cases if the determined probability was less than the level of significance, then null hypothesis (Ho) was rejected and the trend was said to be statistically significant. The smaller the p-value, the more significant the trend was said to be. The level of significance (α) of 5% was used in the study. Five percent (5%) level of significance is mostly used in hydrological studies. Examples include Wilberforce (2007), MOSTI (2013) and Sunil (2011). For the current study MK tau and MK S were used to detect the direction of the trend. A negative value of MK tau (MK S) indicated a decreasing trend and a positive value of MK tau (MK S) indicated an increasing trend. In determining the significance of the LR trends the p-value (α) < 0.05 was also used to define the trend as significant because it is the most commonly used level in most studies including MOSTI (2013) and Fenton and Neil (2012), amongst others. Significance of trends in some stations could not be determined because of gaps in data.

3.4. Linking GHGs emission to climatic and hydrological trends

The main aim of the study was to assess the impacts of GHGs from coal power stations on climatic trends, therefore the focus was on checking the climatic trends both before and after the coal power stations were commissioned and the monitoring of GHGs emissions had been introduced in order to detect if GHGs from coal power stations had some impact in climatic trends behaviour. It was only station 05153208 which was linked to the GHG emissions before and after commissioning of coal power stations because it had extended data that also covered the period when GHGs emissions data was available.

Microsoft Excel software was used to plot graphs of the GHG emission trends. LR was used to investigate the relationship between temperature, rainfall, streamflow data and GHG emissions. LR was used because it is the best method to detect the relationship between variables. LR trends for temperature and rainfall emissions before and after commission of coal power stations were plotted to determine the impact of GHG emissions on climatic trends. The before coal power stations data period was from 1950-1974 and 1925-1974 for both temperature and rainfall respectively, and the after coal power station period was 1975-2016 for both temperature and rainfall. The rainfall data was selected from 1925 to allow enough data to check the trends, as for temperature the source of data only had data that started in 1950. CO_2 was selected as a representative GHG because it stays longer in the atmosphere so its impact is prolonged. Temperature increases as linked to GHG concentrations in the study area was compared with GHG emissions of the chosen coal power stations in order to determine whether the introduction of the coal power stations has contributed to variations in climatic trends of the study area. For example, temperature increases was associated with the persistence and increase of CO_2 content in the atmosphere. It is also used in most climatic trends studies. Various methods for emission control were also recommended.

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Preamble

This chapter discusses results on temperature, rainfall and streamflow trends and their significance using Mann Kendall analysis and linear regression. GHGs trends including links to climate change have also been discussed.

4.2 LR and DMA results

LR graphs showing the relationship of temperature and rainfall at SAWS and neighbouring stations are presented in Annexures B and C, respectively. Figure 4.1 shows graphs for temperature and rainfall stations, with highest R^2 values of 0.969 and 0.77, respectively. MOSTI (2013) stated that the value of R^2 from regression analysis is used to show how strong the correlation and relationship between two variables is and it ranges from 0.0-1. R^2 value of 1.0 means that the correlation is strong and all the points lie on a straight line, whilst R^2 value of 0.0 means that there is no correlation and no linear relationship between two variables. R^2 values of 0.96 and 0.77 indicate excellent and very good relationship between the two stations being correlated, respectively. According to Yan *et al.* (2014), R^2 values of > 0.85 and 0.75-0.85 indicate excellent and very good relationship between variables, respectively. This shows that data from Gemsbokfontein (0516285_W) can be used to estimate temperature data while that of Witbank W stations can be used to estimate rainfall data for SAWS station based on LR. Wijeserkera and Perera (2012) filled missing rainfall data in Attanagalu Oya Basin of Sri Lanka with the use of single and multiple linear regression analysis. Generation of missing data was carried out relative to a common data period in which the data was assumed as homogeneous for computations. R^2 values of 0.91 and 0.88 for Pasyala and Vincit stations, respectively, from regression analysis were considered to be relatively good (Wijeserkera and Perera, 2012). R^2 values from LR results found in the current study for rainfall are lower than the ones in the study by Wijeserkera and Perera (2012) but still indicated good correlation.

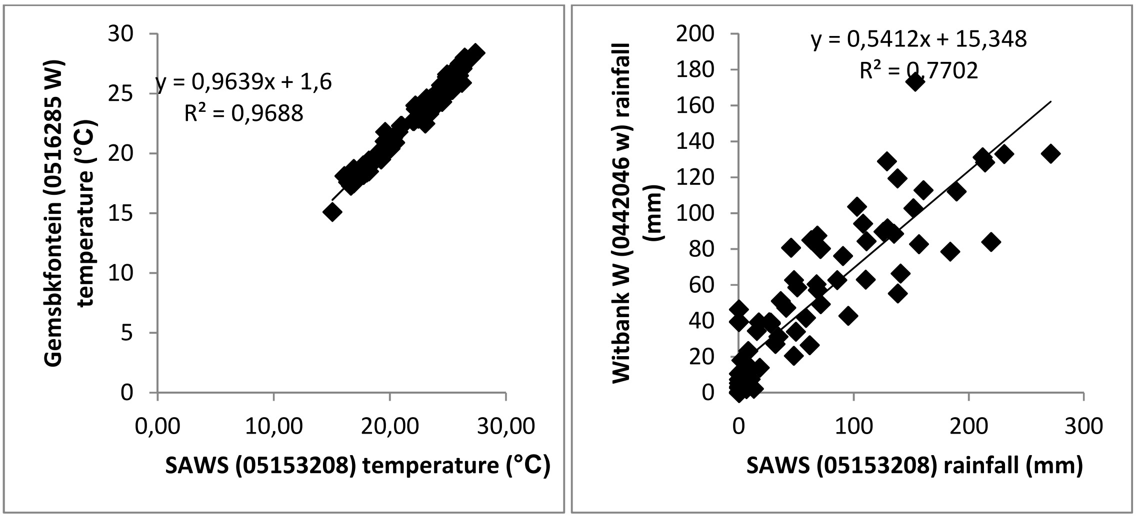


Figure 4.1 LR correlation graphs

Figure 4.2 shows examples of DMA curves which were used to detect the homogeneity and consistency of the data with the two stations. The graphs were able to exhibit a straight line and a slope that represents unchanged proportionality between cumulative rainfall/temperature of the test station and the mean cumulative rainfall/temperature at 3 nearby stations. This follows the theory of the DMC which is based on the fact that a plot of cumulative quantities during the same period exhibits a straight line so long as the proportionality between the two variables remains unchanged and the slope of the line presents the proportionality between the two variables according to Albert (2004). In a study by Hussain *et al.* (2015), DMC showed that Long Lidam and Belaga stations in Linau River Basin in Sarawak had consistent proportionality in the rainfall series. Thus, infilling of missing data was carried out through direct interpolation based on the daily rainfall data of Belaga rainfall station. From the relationship, long term daily rainfall series of 33 years of Long Lidam from 1981 to 2013 was obtained. For the current study, DMC also showed consistent proportionally in both temperature and rainfall long term data of 1950-1993 and 1925-1993, respectively, was obtained.

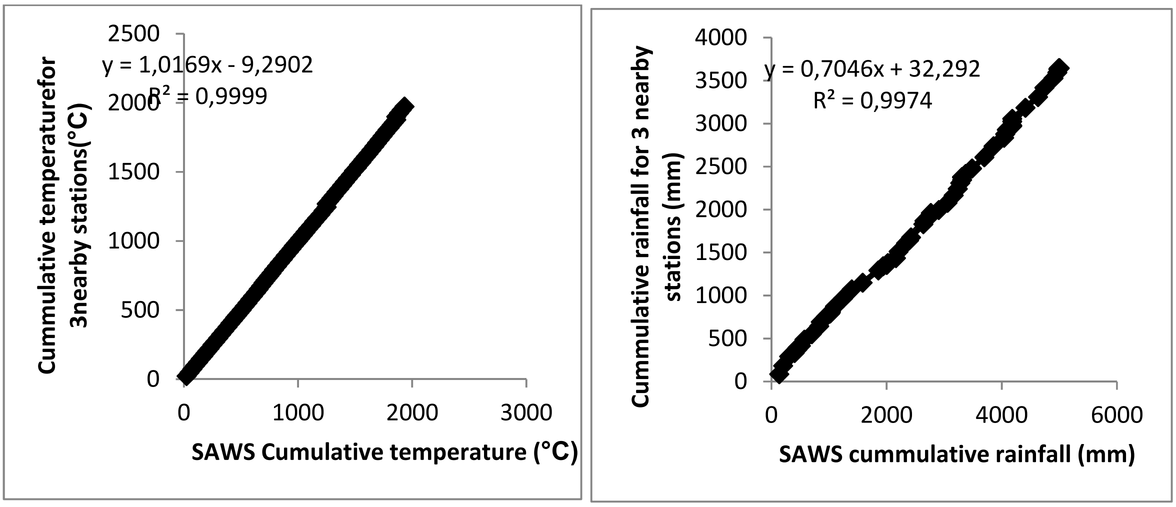


Figure 4.1 DMA consistency graph

R^2 values for both stations were greater than 0.85 showing excellent relationship between the variables according to Yan *et al.* (2014). This shows excellent homogeneity and consistency of rainfall and temperature at SAWS station and the neighbouring stations. Nkuna and Odiyo (2011) obtained R^2 values which ranged from 0.987 to 0.9974 from DMA analysis for rainfall stations in Luvuvhu River Catchment. The R^2 value obtained in the current study of 0.9974 is the same as that for the rainfall analysis while that of temperature is higher than those obtained by Nkuna and Odiyo (2011).

4.3. Trend analysis based on MK and LR methods

4.3.1. Temperature, rainfall and streamflow trends based on MK

The MK results for all temperature stations from the WRC database indicated that there were increasing trends within the study area in the years 1950-2000 which were statistically not significant (Table 4.1). All the p-values are higher than the level 0.05 so the null hypothesis (H_0) which stated that there is no trend in the series was accepted. This means there were no significant temperature trends in these stations. The MK results indicated positive and increasing annual, monthly and seasonal trends for the years 1950-2016 (66 year period) in Witbank area based on the MK S values (Table 4.2) for station 05153208. The p-values were all less than α of 0.05 showing that the trends were statistically significant, therefore H_0 was rejected (meaning there is a significant increase in the series). Table 4.3 shows decreasing trends for rainfall stations Witbank Mag/Pow, Witbank1 and Witbank W, whilst Witbank Mun shows an increasing trend. Thus, decreasing trends were dominating in the study area. Witbank Mag/Pow and Witbank1 showed statistically significant decrease in rainfall trends. MK results indicated negative and decreasing annual, monthly and seasonal trends for the years 1925-2016 (91 year period) in Witbank area based on the MK ZS values (Table 4.4). The p-values were all greater than α of 0.05 showing that the trends were not statistically significant. Therefore H_0 was accepted.

Table 4.1 MK trend test for temperature data from WRC database

Station name	**Scale**	**MK tau**	**MK S**	**Trend**	**p-value (two-tailed)**	**Statistical significance**
Delmas pioneer	Monthly	0.032	6016	Increasing	0.234	Not significant
Delmas witklip	Monthly	0.010	4387	Increasing	0.714	Not significant
Bronkhorstproot	Monthly	0.008	1439	Increasing	0.776	Not significant
Kanhyms-Investments	Monthly	0.011	2113	Increasing	0.676	Not significant
Gemsbkfontein (0516285 W)	Monthly	0.015	2218	Increasing	0.661	Not significant
Gemsbkfontein	Monthly	0.015	2867	Increasing	0.571	Not significant
Bethalwildebeesfontein	Monthly	0.010	1856	Increasing	0.714	Not significant

Table 4.2 Yearly, monthly and seasonal MK trend test for temperature data for station 05153208.

Trend period	MK tau	MK S	Trend	p-value (two-tailed)	Statistical significance
Yearly	0.279	599	Increasing	0.001	Significant
Monthly	0.027	21764	Increasing	0.003	Significant
Seasonal	0.136	1794	Increasing	< 0.0001	Significant

Table 4.3 MK trend test for rainfall data

Station name	Scale	MK tau	MK S	Trend	p-value (two-tailed)	Statistical significance
Witbank Mun	Monthly	0.013	5277	Increasing	0.562	Not significant
Witbank k1	Monthly	-0.091	-37072	Decreasing	< 0.0001	Significant
Witbank Mag/Pow	Monthly	-0.081	-32856	Decreasing	0.000	Significant
Witbank W	Monthly	-0.014	-5702	Decreasing	0.531	Not significant

Table 4.4 Yearly, monthly and seasonal Mk trend test for rainfall data for station 05153208

Trend Period	MK tau	MK S	Trend	P value (two tailed)	Statistical significance
Yearly	-0.100	-411	Decreasing	0.160	Not significant
Monthly	-0.029	-14617	Decreasing	0.172	Not significant
Seasonal	-0.008	-170	Decreasing	0.782	Not significant

For streamflow gauging station B2H004, the MK results indicated increasing trends for all annual, monthly and seasonal streamflow for the years 1985-2015 (30 year period) based on the MK tau values (Table 4.5). The p-values indicated a non-significant increase in the annual and seasonal streamflow trends, whilst the monthly streamflow trends indicated an increasing trend which was not significant for stations B2H004 and B2H007.

Table 4.5 MK trends for streamflow data

Station name	**Scale**	**MK tau**	**MK S**	**Trend**	**P value (two tailed)**	**Statistically significant**
B2H004	Yearly	0.071	31	Increasing	0.596	Not significant
	Monthly	0.113	8200	Increasing	0.001	Significant
	Seasonal	0.094	274	Increasing	0.066	Not significant
B2H007	Yearly	0.127	38	Increasing	0.392	Not significant
	Monthly	0.070	4657	Increasing	0.046	Significant
	Seasonal	0.046	107	Increasing	0.353	Not Significant

The streamflow gauging stations are located upstream and in a high altitude area where relatively high rainfall which may lead to increased streamflow is expected. They are also in a neighbouring quaternary catchment to that dominated by coal power stations (see Figure 3.1). The results thus, indicate that the streamflow from these stations is not affected by the decreasing rainfall trends which were identified in station Witbank 1, Witbank Mug/Pow and Witbank W. This suggests that rainfall is not the only factor affecting streamflow in the study area.

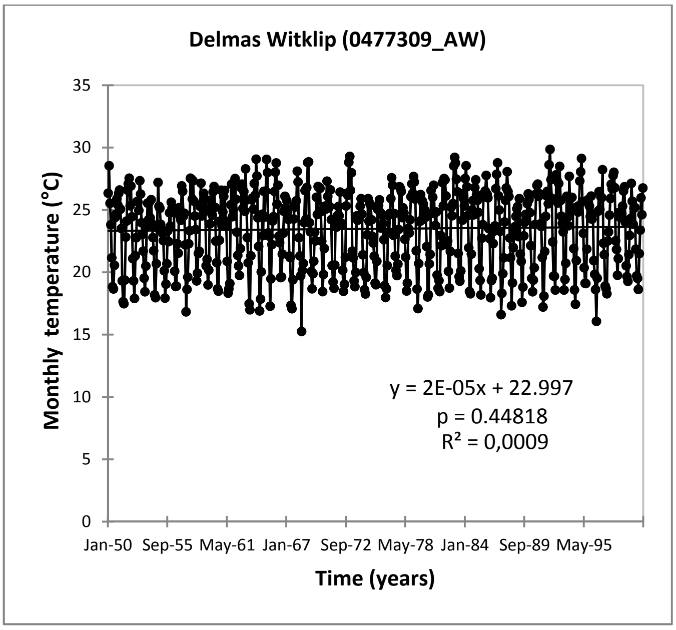
4.3.2 Temperature, rainfall and streamflow trends based on LR

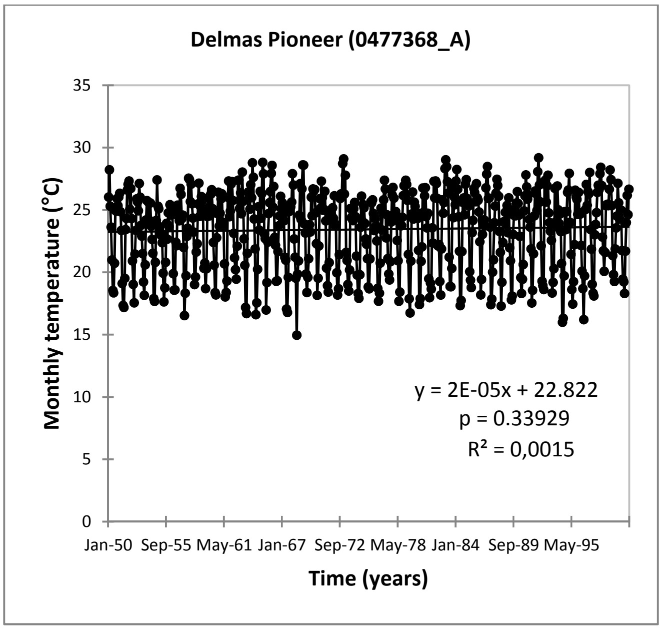
Figure 4.3 shows monthly LR results for the temperature stations within the study area from 1950-2000. The linear trend lines show increasing trends in all the temperature stations. All the p-values were greater that a level of 0.05, therefore there was no statistically significant trend in the series. Figure 4.4 indicates an increasing trend in the average annual temperature for the year 1950 to the year 2016. The linear trend indicates a clear increase in the average annual temperature. The p-value of 0.000027 is lower than 0.05 indicating a significant increasing trend in the annual temperature.

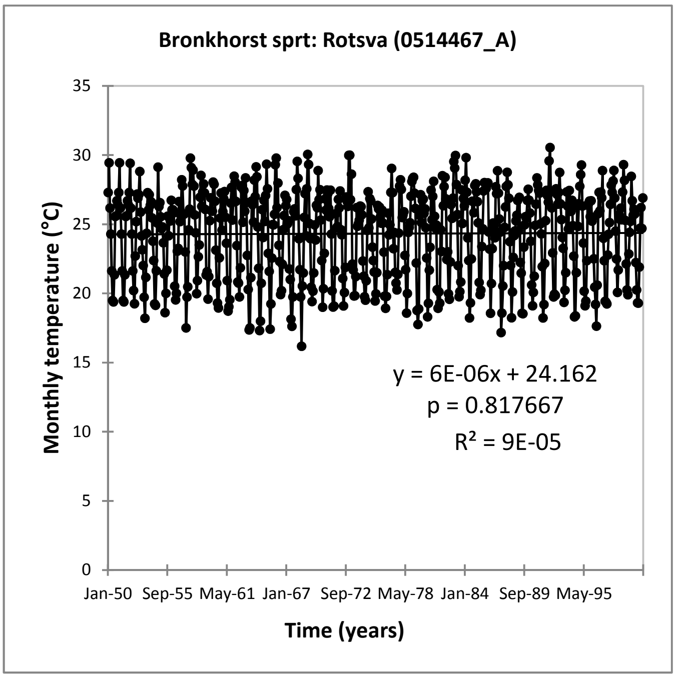
Figure 4.5, which is a plot of monthly temperature data for station 05153208, shows an increasing trend in temperature from the year 1950 to the year 2016. The p-value could not be calculated using LR because of gaps in the data, therefore the significance of the monthly LR trend for this station could not be determined. Figure 4.6 agrees with the MK trend test that there has been an increasing trend in seasonal temperature in Witbank area over the hydrological years 1950-2016. The LR trend line for seasonal temperature shows an increasing trend. The seasonal temperature data also had gaps as a result the p-value could not be obtained through LR analysis. Increasing temperature trends identified in Figures 4.4 to 4.6 are similar to those identified by MK method.

Mackellar *et al.* (2014) demonstrated that maximum and minimum temperatures have increased significantly at every station which was chosen both when analysed annually and for all four seasons of the year. The study included Witbank area. Kruger and Shongwe (2004) conducted a study on determining temperature trends in South Africa for the years 1960-2003. The study found positive or increasing trends in the mean annual maximum temperature of a total of 23 out of 26 stations which were chosen, with 13 of them showing significant trends. The results of the current study were similar to the results found by Mackeller *et al.* (2014) and Kruger and Shongwe (2004).

Figure 4.7 shows mothly LR results for the rainfall stations within Lynch (2004) database from the year 1925-2000. The linear trend lines show decreasing trends in rainfall except for Witbank Mun showed a non significant increasing trend. All the p-values are lower than 0.05 except for Witbank Mun and Witbank W with p-values of 0.39 and 0.10, respectively. Witbank W showed a non significant decreasing trend.







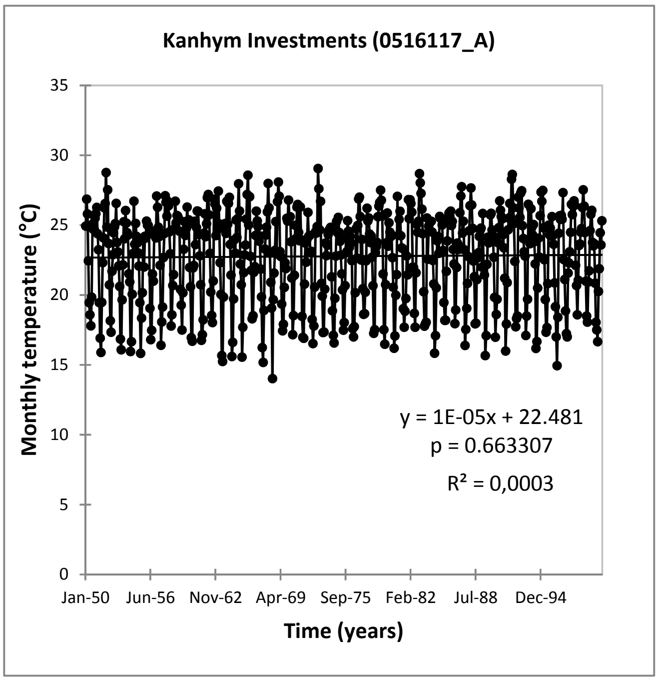


Figure 4.3 (a) LR results for stations 0477309_AW, 0477368_A, 0514467_A, and 0516117_A.

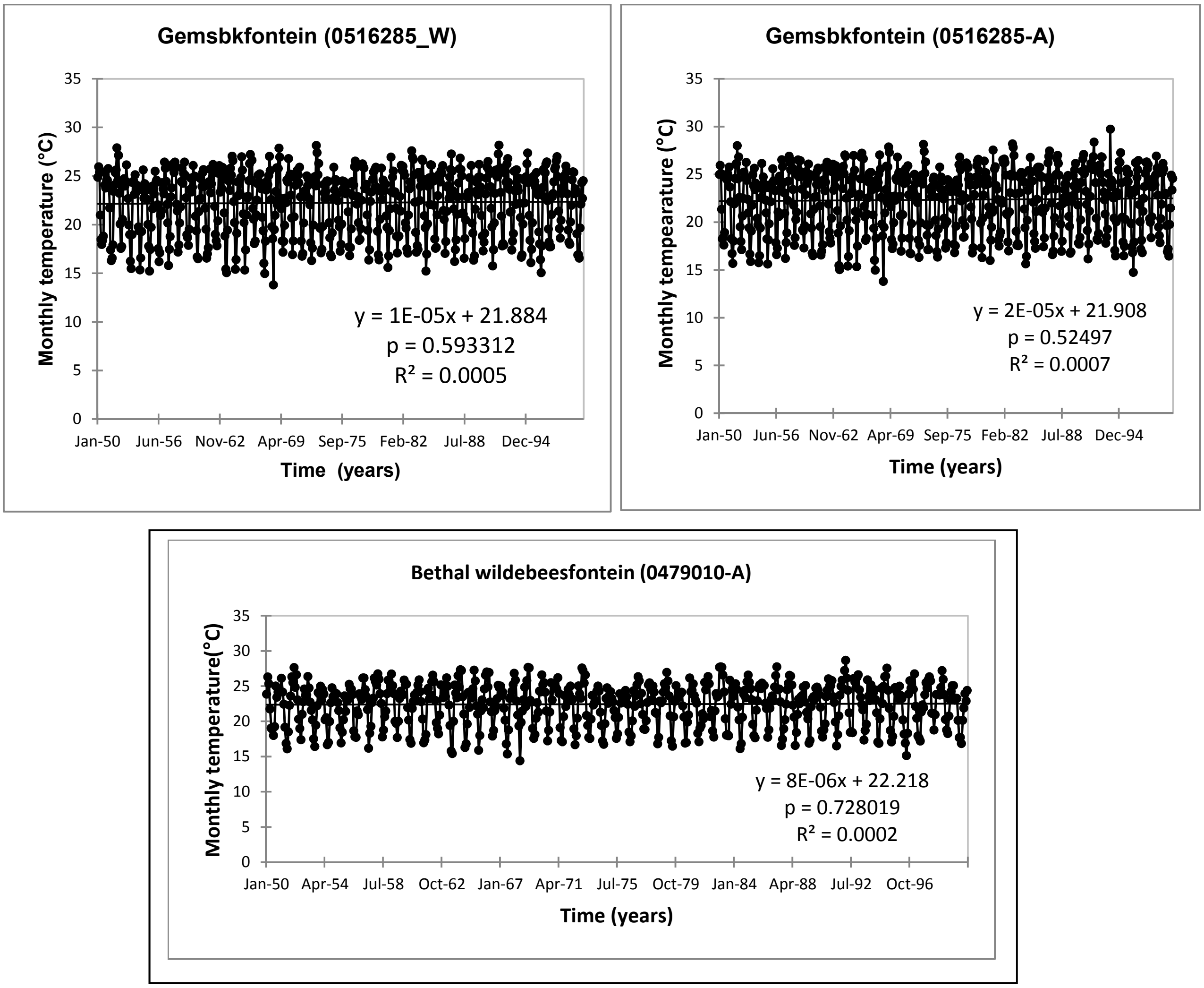


Figure 4.3.(b) LR results for stations 0516285_W, 0516285_A and 0479010_A.

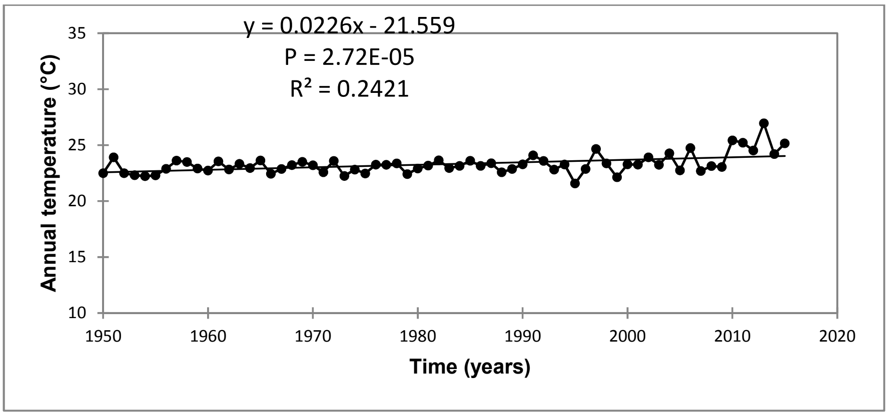


Figure 4.4. SAWS extended data for annual temperature LR trend

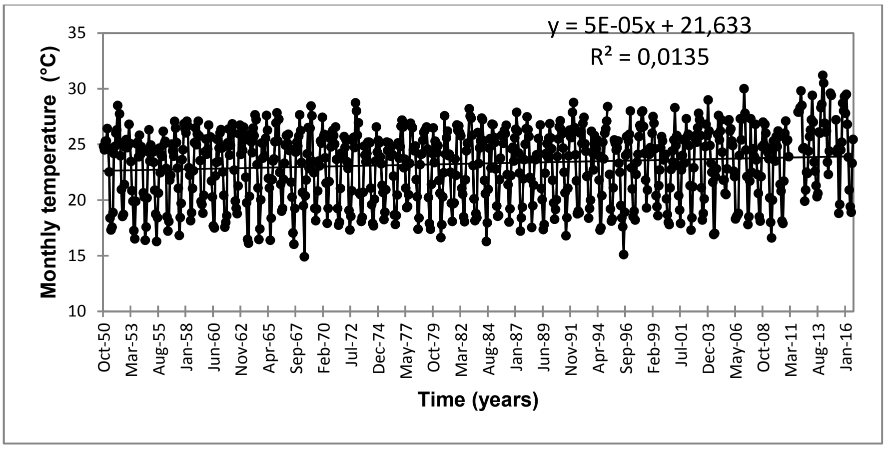


Figure 4.5 SAWS extended data for monthly temperature LR trend

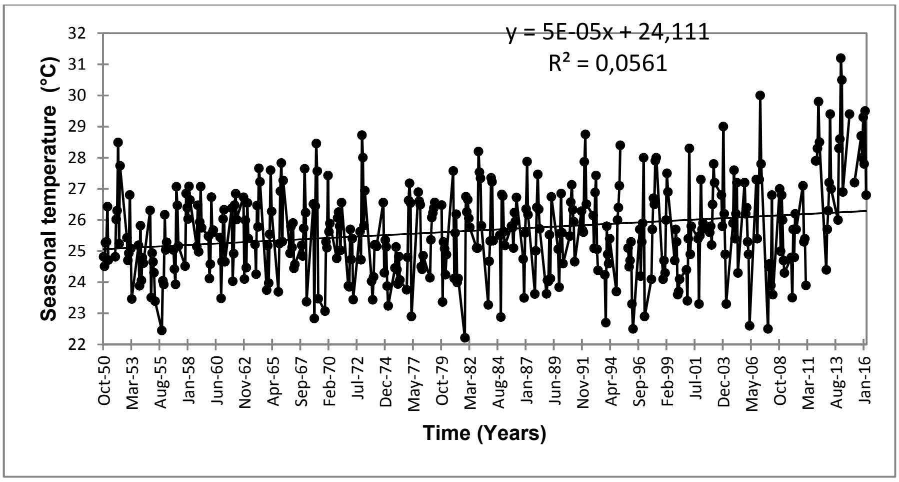


Figure 4.6. SAWS extended data for seasonal temperature LR trend for station 05153208.

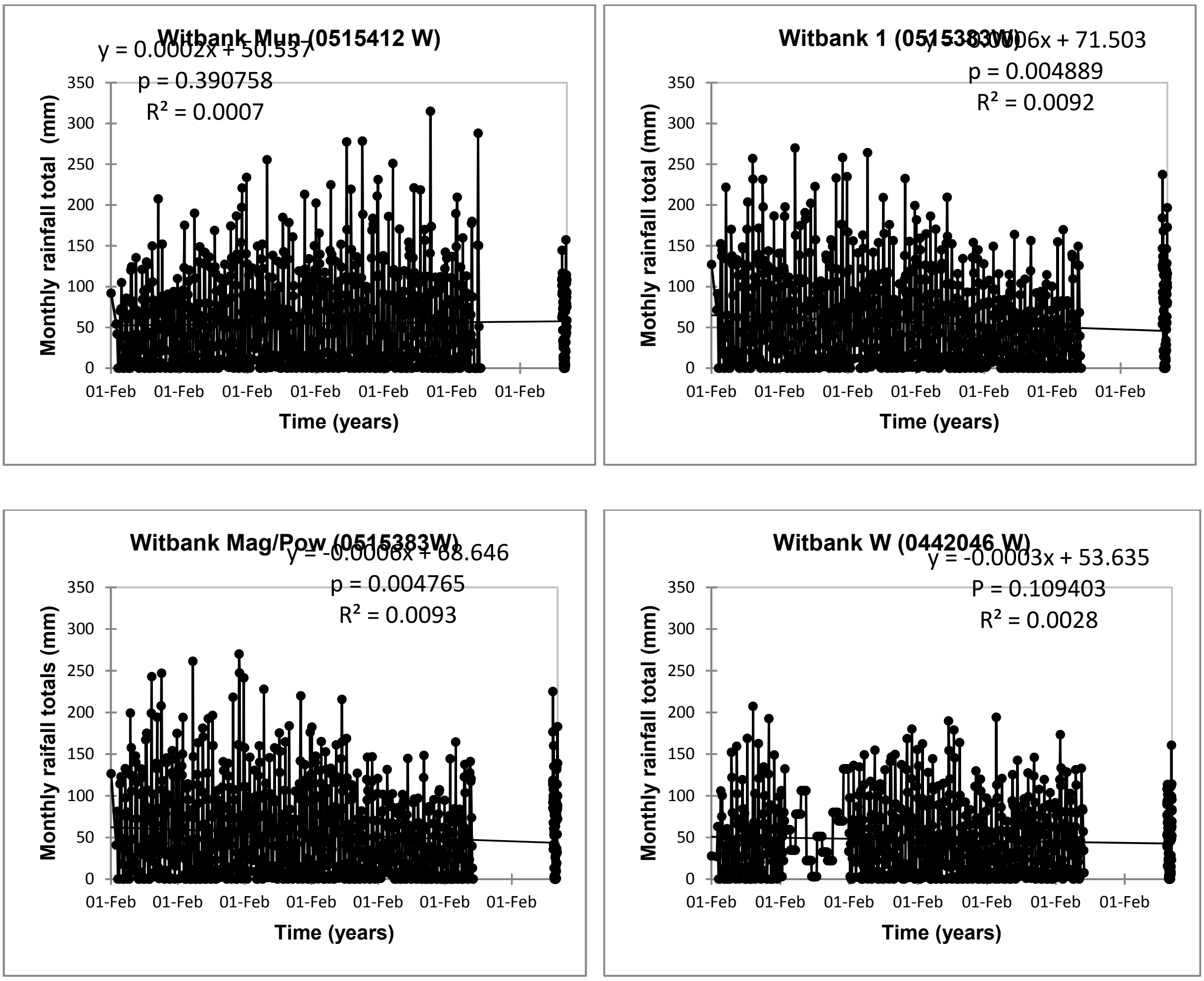


Figure 4.7. LR trends for rainfall station from lynch database.

Figure 4.8 shows that there has been a decreasing trend in the annual rainfall of Witbank area from the hydrological years 1925-2015. The LR indicated a non-significant decreasing trend (p-value = 0.092759 greater than a level of 0.05) in the rainfall pattern of Witbank area. The MK trend test indicated a non-significant decreasing trend (p-value = 0.160). There was a decreasing trend in monthly rainfall in station Witbank W from the year 1925-2016 (Figure 4.9). LR results for seasonal rainfall showed a slight decreasing trend (Figure 4.10). It was also difficult to determine the significance of the monthly and seasonal trends as the p-value could not be obtained from the LR as there were gaps in the data used for analysis.

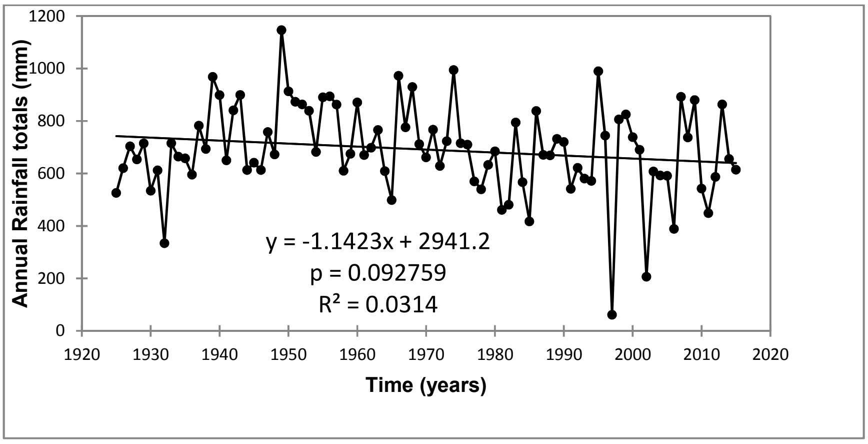


Figure 4.8. Annual rainfall LR trend for station 05153208.

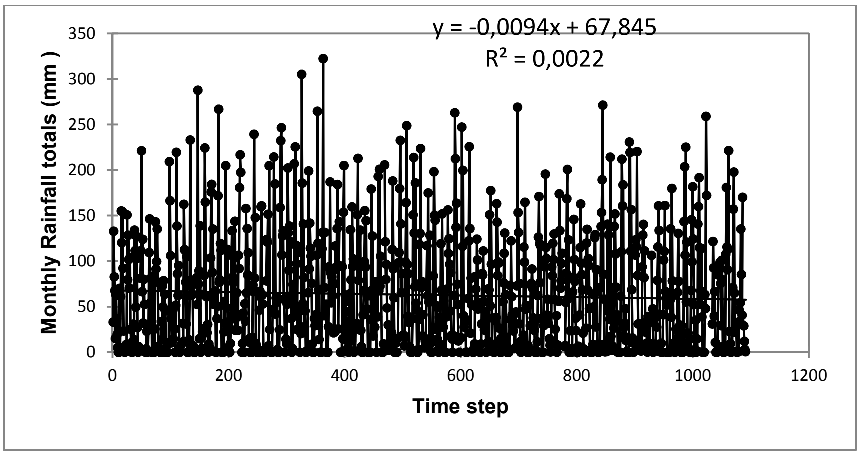


Figure 4.9. Monthly rainfall LR results

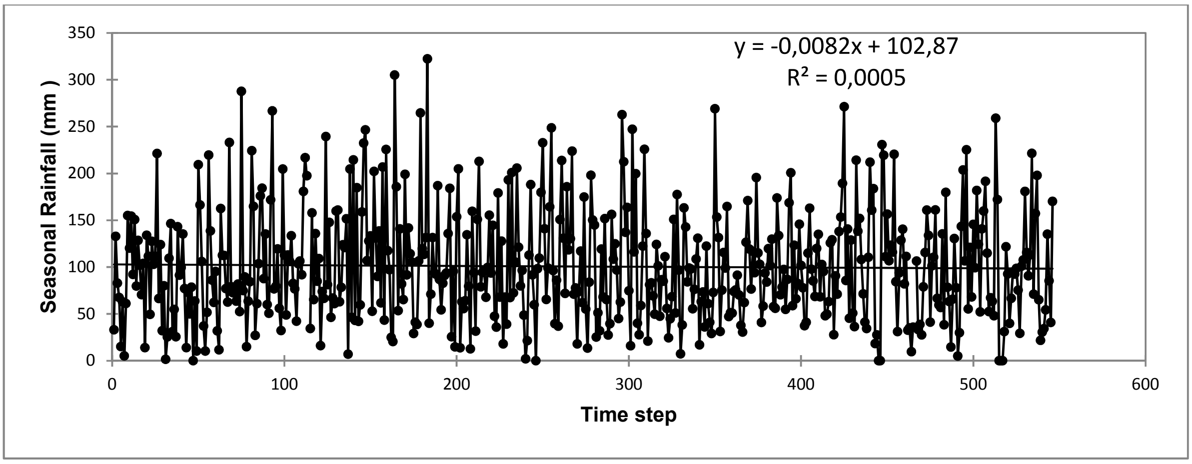


Figure 4.10. Seasonal rainfall LR results

Figure 4.11 shows the annual and monthly LR trends for station B2H004 for the years 1985-2015 and 1984-2016 for seasonal streamflow trends. The results gave p-values of 0.610, 0.141 and 0.284 for the annual, monthly and seasonal streamflow trends, respectively, which indicated non-significant increasing trends. The streamflow data for all the annual, monthly and seasonal trends had some gaps which were removed in order to run the LR model. For seasonal streamflow, the month of October and November 2009 were excluded in the analysis. For annual streamflow, the year 1992 was removed because of gaps which could not allow the LR model to run, the LR model is not able to analyse data with gaps. For monthly data, March 1993 was removed from the analysis and for streamflow data November 1984, March 1993 and March 2016 were removed because there were gaps which could not be patched because of lack of data in the study area. The removal of the gaps in data affected the significance of the trends for example, where the data was to be statistically significant, the data may result in a non-significant result either increasing or decreasing based on the statistical data provided in running the model.

Mackellar *et al.* (2014) analysed rainfall trends of 72 SAWS stations for the year 1960-2000, with less than 20% missing data. The results indicated that overall trends in rainfall totals were weak and non-significant but there was a tendency towards a significant decrease in the number of rain days. This study also indicated that there was mixed signals in terms of changes in rainfall totals of Mpumalanga province, with the trends being generally insignificant. The current study also showed similar results in terms of decreasing rainfall trends in Witbank area with the annual trend giving a P-value of 0.09 which showed a non-significant decrease in rainfall.

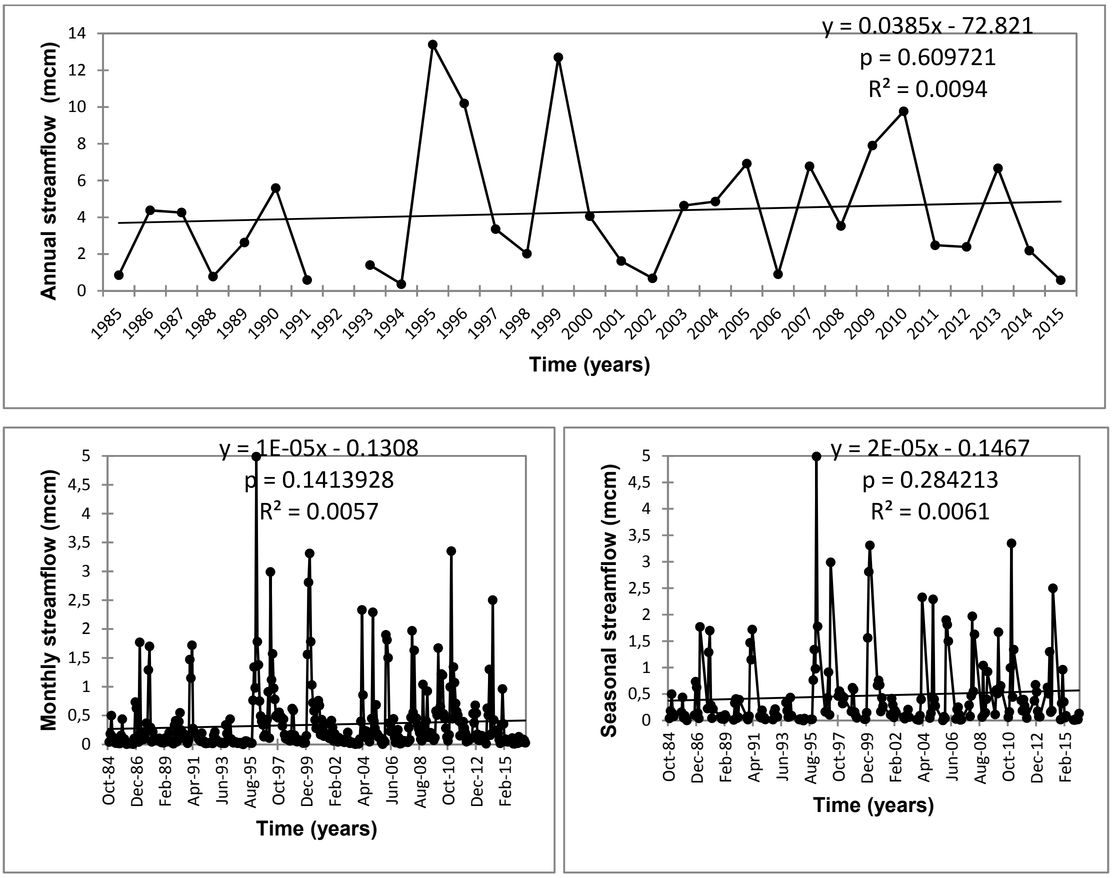


Figure 4.11. Annual, monthly and seasonal streamflow LR results for B2H004

Figure 4.12 shows annual, monthly and seasonal streamflow LR trends for station B2H007 for the years 1985-2011. The results gave p-values of 0.461 and 0.777 which indicated non-significant increasing trends for the annual and seasonal trends, respectively. The monthly streamflow data failed to produce significance test results from the LR model because of too many gaps in the data. The annual and seasonal data indicated that there was no significant trend in the series as all their p-values are higher than the level of 0.05. The streamflow data for both annual and seasonal trends had some gaps which were removed in order to run the LR model. Unfortunately the monthly data had many gaps which could not be patched. For annual streamflow, 2 years were excluded from the analysis (2008 and 2009) because of missing data. For seasonal streamflow, the month of October and November 2009 were excluded in the analysis. The current study showed non-significant increasing trends for LR for stations B2H004 and B2H007 in yearly and seasonal time scales. The MK trend test also showed similar results with non-significant increasing trend for both the stations B2H004 and B2H007 in yearly and seasonal scales, except for the monthly scales which showed significant streamflow trends for B2H004.

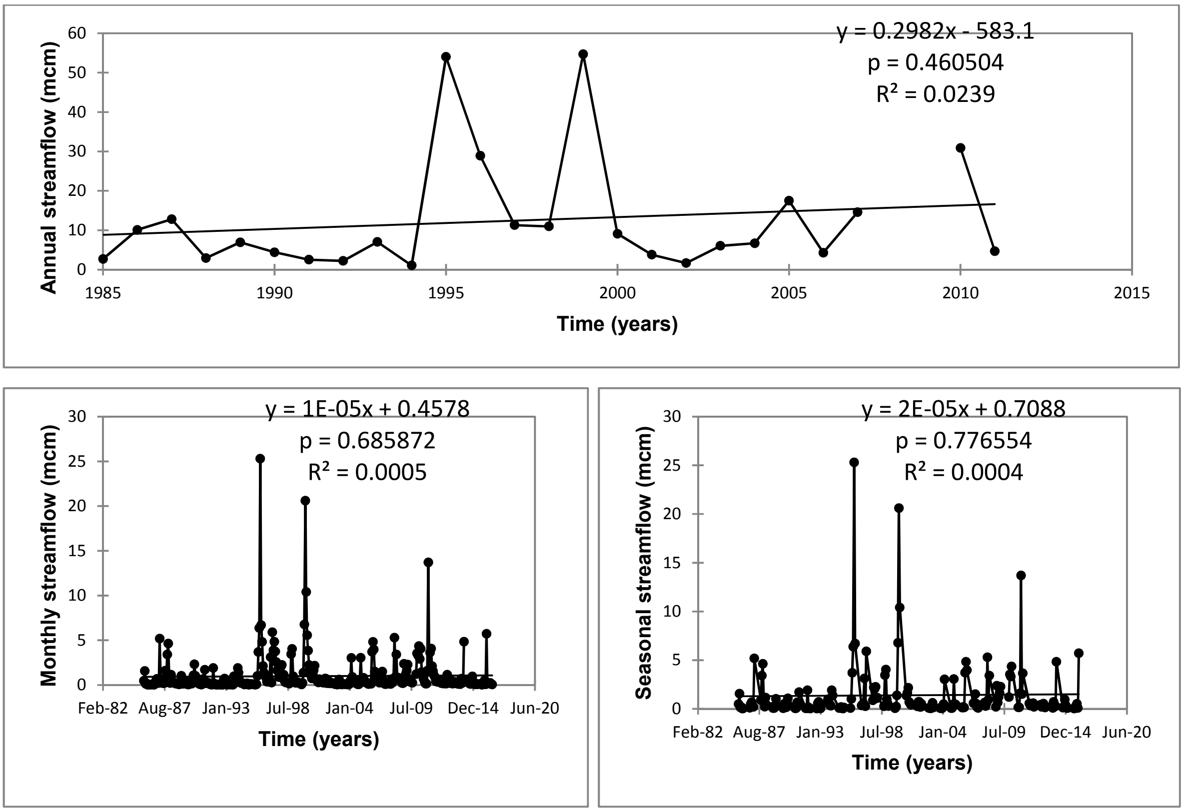


Figure 4.12. Annual, monthly and seasonal streamflow results for B2H007

4.4 GHGs emission trends and links to climate change

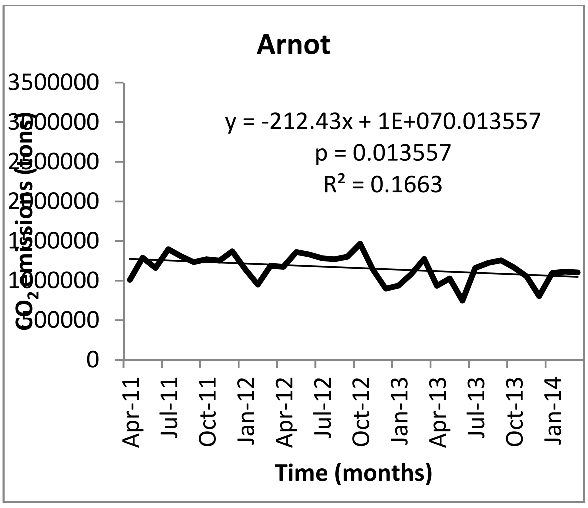
Table 4.6. shows temperature and rainfall trends before and after the commissioning of coal power stations. The MK results before comissioning of the coal power stations showed increasing non-significant trends in monthly and annual temperature. After the comissioning of the plants, there was a statistically significant increase in monthly and annual temperature trend (Table 4.6.) There was a non-significant increase in monthly rainfall trend before the introduction of coal power stations whilst the yearly results indicated a significant increasing trend. Monthly and yearly rainfall trends after the coal power stations were commissioned both indicated non-significant decreasing and increasing trends, respectively.

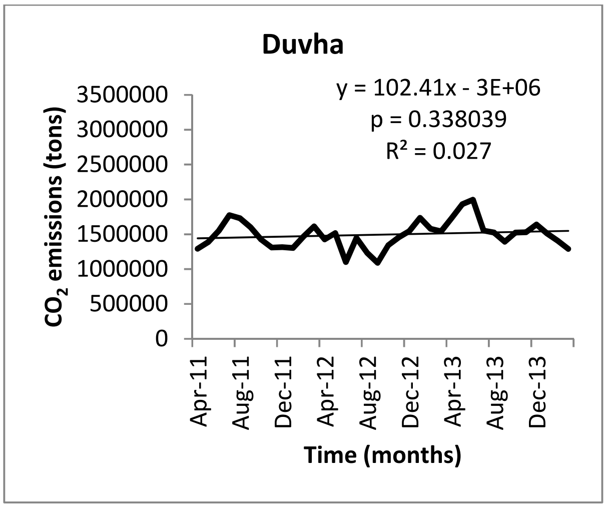
Table 4.6. MK results for temperature and rainfall before and after coal power stations started operating.

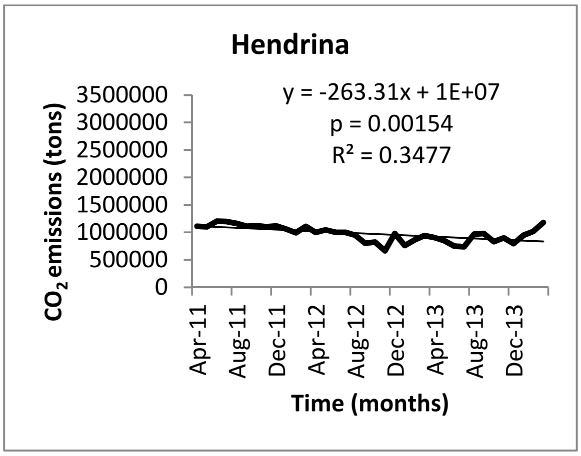
Variable	**Trend period**	**MK tau**	**MK S**	**Trend**	**p-value (two tailed)**	**Alpha (α) Significance Level**	**Null hypothesis**	**Statistical significance**
Temperature	Monthly (Before)	0.009	380	Increasing	0.819	0.05	Accepted	Not Significant
	Yearly (Before)	0.080	24	Increasing	0.591	0.05	Accepted	Not Significant
	Monthly (After)	0.094	16142	Increasing	0.002	0.05	Rejected	Significant
	Yearly (After)	0.283	232	Increasing	0.009	0.05	Rejected	Significant
Rainfall	Rainfall Monthly (Before)	0.032	46444	Increasing	0.273	0.05	Accepted	Not significant
	Yearly (Before)	0.200	245	Increasing	0.041	0.05	Rejected	Significant
	Monthly (After)	-0.021	-2277	Decreasing	0.497	0.05	Accepted	Not significant
	Yearly (After)	0.046	38	Increasing	0.678	0.05	Accepted	Not significant

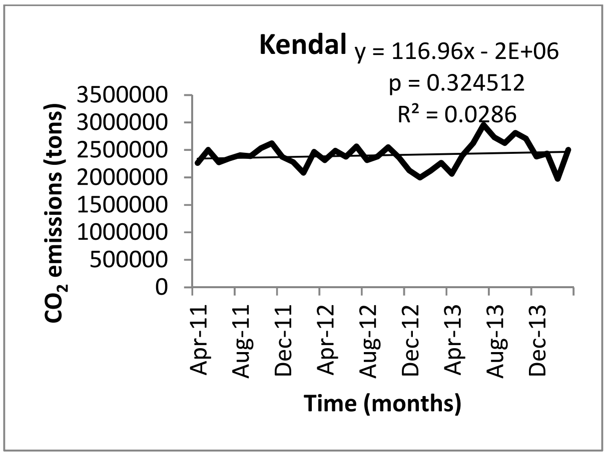
Coal power stations Arnot and Hendrina showed significant decreasing trends in CO_2 emissions whilst Duvha and Kendal showed non-significant increasing trends, and Matla coal power station showed a decreasing non-significant trend (Figure 4.13). There were no significant trends for the power stations Duvha, Kendal and Kriel as all their p-values were greater than 0.05. In South Africa, Minimum Emission Standards (MES) were promulgated in 2005 to take effect in April 2015. During 2013 many industries, including Eskom applied for postponement, and in some cases, exemption from the standards with cost cited as the major hurdle preventing compliance (Pretorius *et al.*, 2015). Hence, increasing trends in some stations though mostly non-significant statistically are likely to be due to the fact that emissions standards are still in the process of being implemented. The decreasing trends are expected because the data that was used in the analysis was from the months April 2011 to March 2014. This was after the minimum source emission standards were published in April 2010 in terms of the National Environmental Management Air Quality Act according to Eskom (2012), to force coal power stations to comply with such standards. Thus, ESKOM was already reducing its emissions in Arnot, Hendrina and Matla coal power stations.

According to Pretorius *et al.* (2015), absolute CO_2 emissions increased by 15% (from 200 to 230 Mtpa) during the 2006-2012 period in South Africa, meaning that before the decrease in emissions there was likely an increasing trend in the CO_2 emission which partially supports the significant increasing trends in temperaure for the years 1950-2016. CO_2 stays longer in the atmosphere and increases temperature, according to Sabouni (2013).









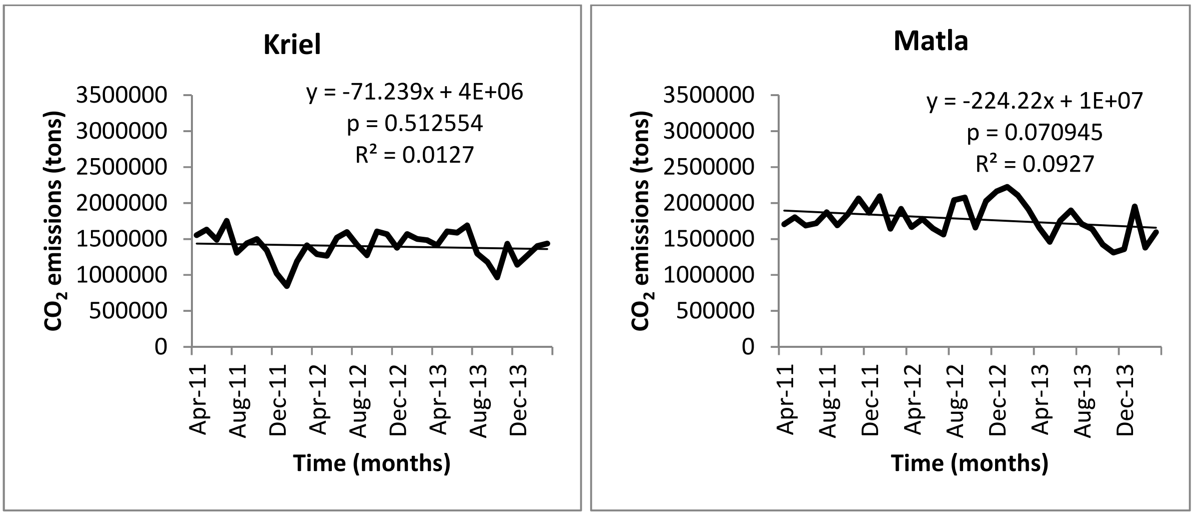


Figure 4.13. LR trends for Arnot, Duvha, Hendrina, Kendal, Kriel, and Matla coal power stations.

LR graphs (Figure 4.14) indicate average annual and monthly temperature trends within the study area. Figures 14.4(a) and (c)) show monthly and annual temperature trends before the coal power stations were commissioned, respectively. The annual temperatures before commissioning ranged from 22.2 to 23.9°C (1.7°C) whilst that after the commissioning of the coal power stations ranged from 21.5 to 26.9°C (5.4 °C) (Figure 4.14). The monthly temperature before commissioning ranged from 14 to 28.7°C (14.7) whilst that of after the commissioning of the coal power stations ranged from 15.1 to 31.2°C (16.1) (Figure 4.14).

The average annual temperature before the commissioning of coal power stations gives a p-value of 0.53 which shows non-significant trend as it is greater than 0.05 but the average annual temperature after the commissioning of the coal stations gives a p-value of 0.000364 which is lower than 0.05, which means that there was a significant increase in temperature after the introduction of coal power stations which further confirms that temperature increased after coal power stations were commissioned and could be linked to GHGs emissions.

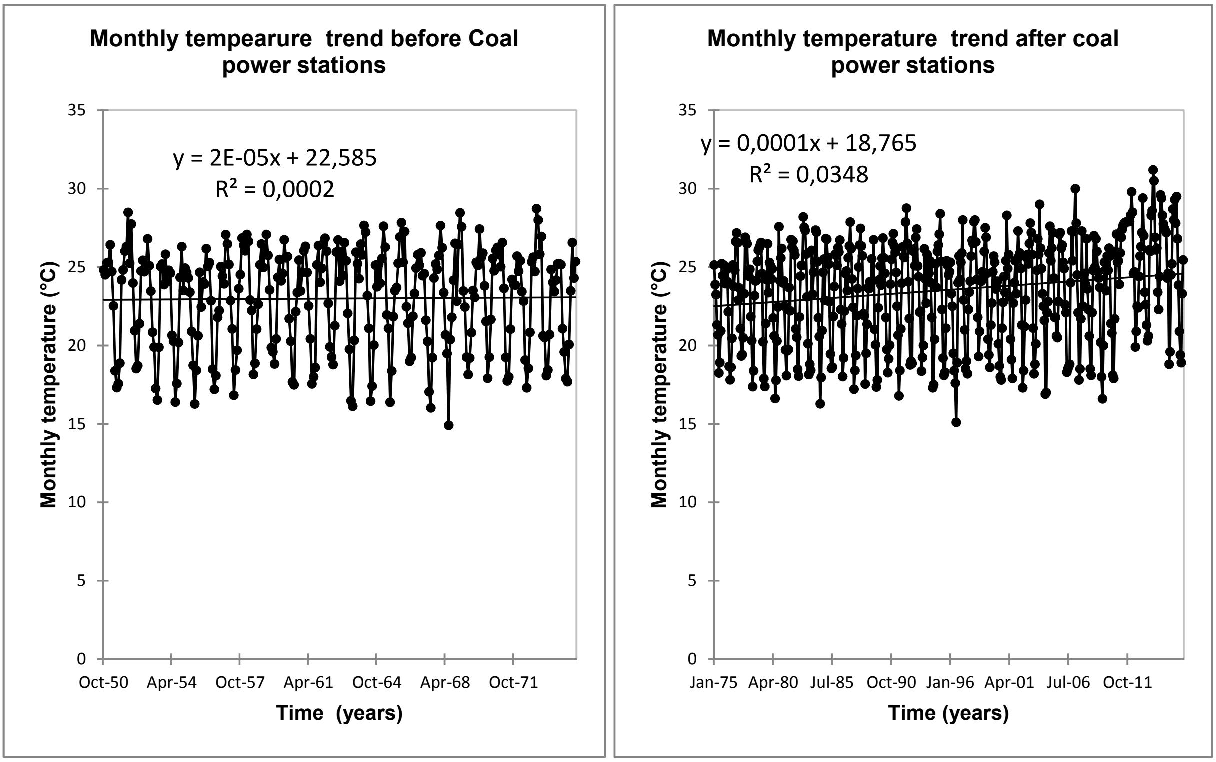


Figure 4.14 (a): Monthly temperature trend for SAWS station extended data before and after the introduction of coal power stations.

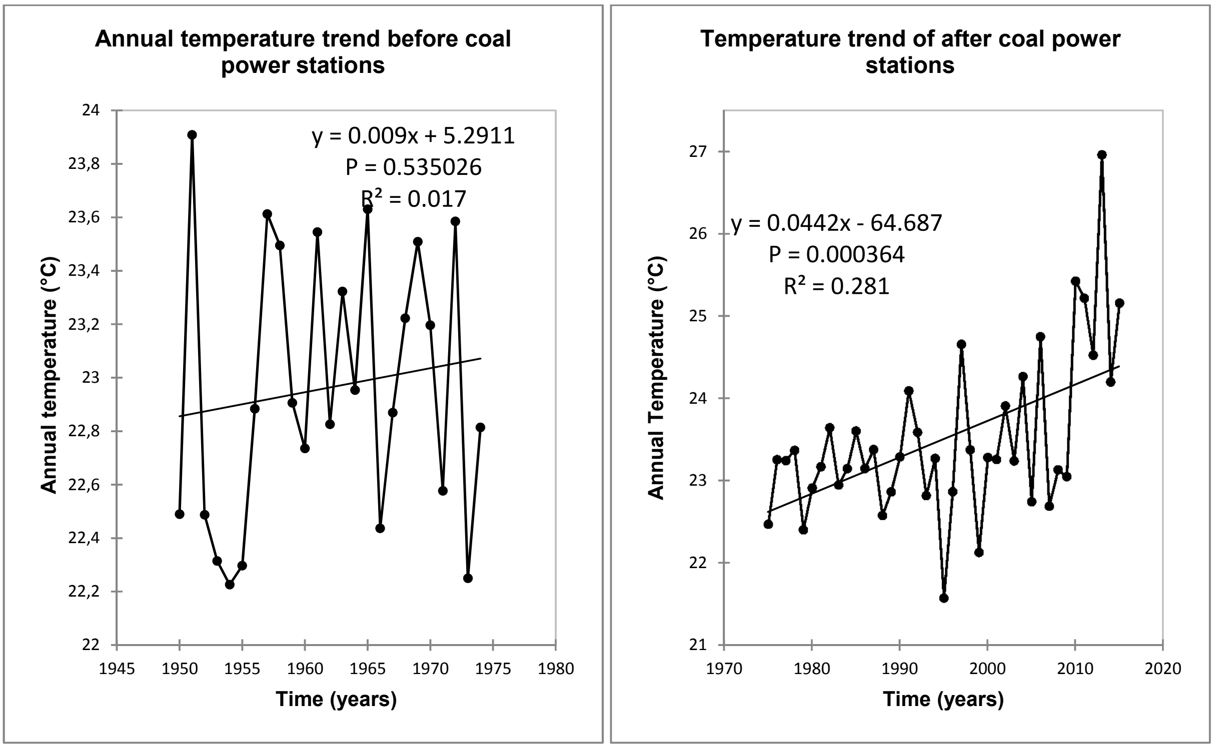


Figure 4.14(b): Annual temperature trend for SAWS station extended data before and after the introduction of coal power stations.

Figure 4.15 indicates the annual rainfall trends of both before and after the commissioning of the coal power plants within the study area. There was increasing and decreasing trends before and after the commissioning of coal power stations. For before coal power plants were introduced p-value was 0.034 which shows a significant increasing trend as it is less than 0.05. The p-value for the trend after commissioning of the coal stations gives a p-value of 0.838 which is greater than 0.05, meaning that there was no significant trend in the annual rainfall pattern after the introduction of coal power stations. The significance of the monthly rainfall trends before and after the commissioning of coal power stations could not be detected because of multiple gaps within the data used.

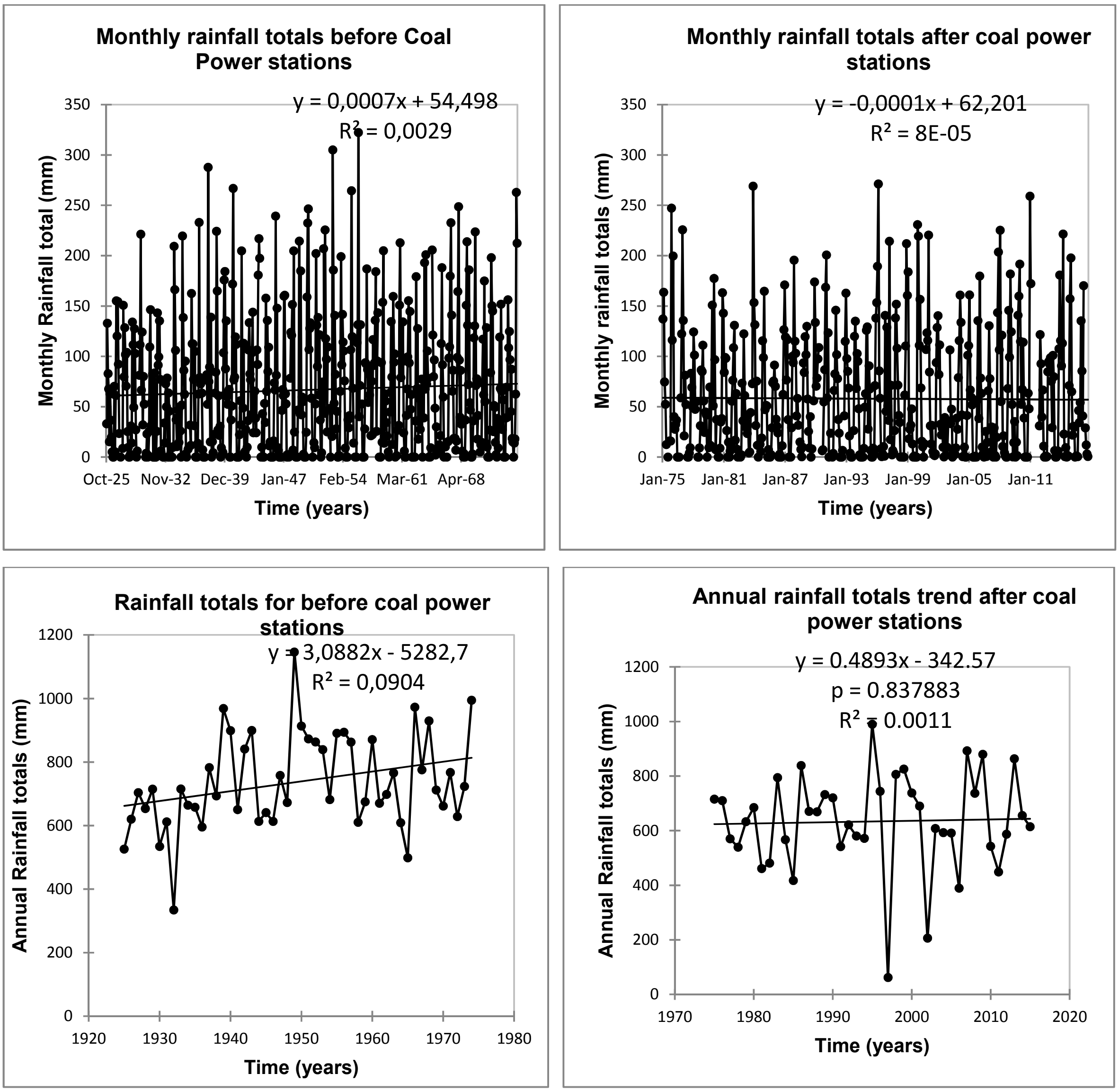


Figure 4.15. Rainfall trends for SAWS (05153208) extended data before and after the introduction of coal power stations.

4.5 Suggested coal-fired power station emission control strategies

In general, there are several approaches that can be adopted to reduce the total CO_2 emission into the atmosphere. These include reduction in energy intensity by efficient use of energy, reduction of carbon intensity by using alternatives to fossil fuels like hydrogen and renewable energy, and enhancement of CO_2 sequestration by developing new carbon capture technologies (Yang *et al*,. 2008).

In relation to the current study the following approaches are recommended:

CCS is a suitable approach because it involves capturing CO_2 at power plants and other industries before it is emitted into the atmosphere and transports CO_2 to suitable disposal locations or stores CO_2 underground or utilises CO_2 to retrieve high-value products. This approach helps protect the atmosphere against degradation of the Ozone layer.

Solar energy can reduce the weight on electricity demand at household level and help to enhance fuel consumption efficiency by reducing energy intensity.

Alternatives to fossil fuels such as hydrogen, biomass, and nuclear energy are not in the suitable in the study area. These energy sources are not commercially viable as they cannot meet energy demands and are still being developed (Sauboni, 2013). Hydropower on the other hand requires water in ample quantity, if not so, the power plants cannot produce electricity. It also impacts on water quality, flow and can cause low dissolved oxygen levels in the water, a problem that is harmful to riparian (riverbank) habitats Smit (2011). Another disadvantage is that South Africa is a water scarce country and hydropower requires water in ample quantity, if not so, the power plants cannot produce electricity. They are also prone to drought Smit (2011). Witbank is located in a water scarce country making it difficult to implement this strategy.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

The study investigated the impacts of GHGs from coal power stations on climatic and hydrological trends in the Witbank area. Using temperature, rainfall and streamflow data, hydro-climatic trends and their significance were determined at monthly, seasonal, and annual scales using LR and MK trend test methods. GHGs emissions trends were also determined using both the MK and LR methods using data from the Eskom's sustainability report hence, the main objective (Section1.4) was met. GHGs emissions had impacts of temperature trends which indicated a statistical significant increase after the introduction of coal power stations. Temperature trends increased with time whilst rainfall trends decreased as the temperature increased and the streamflow trends increased. Increased streamflow trends could be due to the location of the streamflow gauging stations being upstream the rainfall gauge stations, meaning that the decreasing rainfall trends did not have much impact on the streamflow in the area. Rainfall decreases could be the results of high temperatures causing drought. The study revealed that GHGs from coal power stations had impacts on the hydro-climatic trends in Witbank area by linking GHGs emissions with temperature, showing the extent to which temperature has significantly increased. The study showed that the temperature increased by 3.7 and 1.4 after the commissioning of coal power stations on annual and monthly basis, respectively. Both these increases were detected to be statistically significant using both MK and LR methods, though the LR could not detect of significance monthly trends because its inability to determine significance of trends from time series gaps. Several strategies that can be adopted for emission control were reviewed and suggested.

5.2 Recommendations

The study recommends that more rainfall, streamflow and temperature monitoring stations should be introduced in the area for similar studies in the future and continuous monitoring of hydro-climatic data in order to determine long-term impacts of GHGs emission on climatic variables. More research must be done on alternative sources of energy such as wind and solar energy to check their suitability and applicability in South Africa. It is also recommended that the Kyoto protocol be revised in a manner that would better suit both the environment and the country hence, promoting environmental sustainability and economic development.

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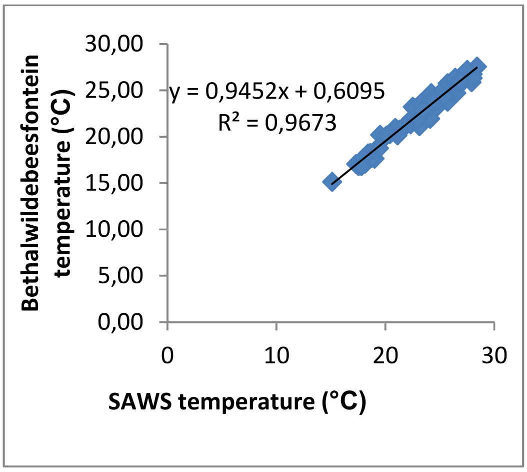
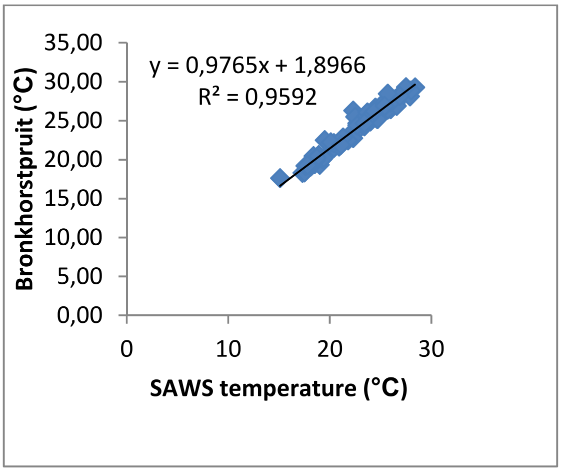
ANNEXURES

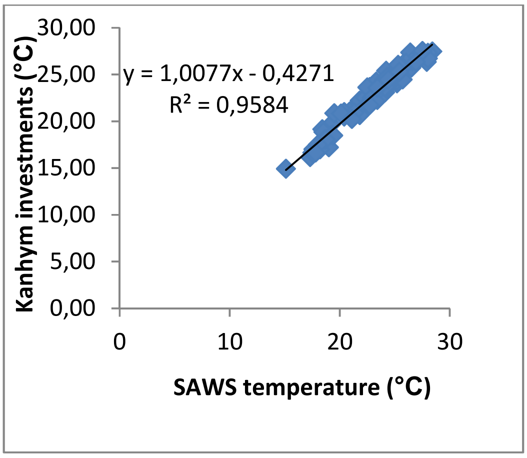
ANNEXURE A: GPS COORDINATES OF ALL THE SELECTED STATIONS WITHIN THE STUDY AREA

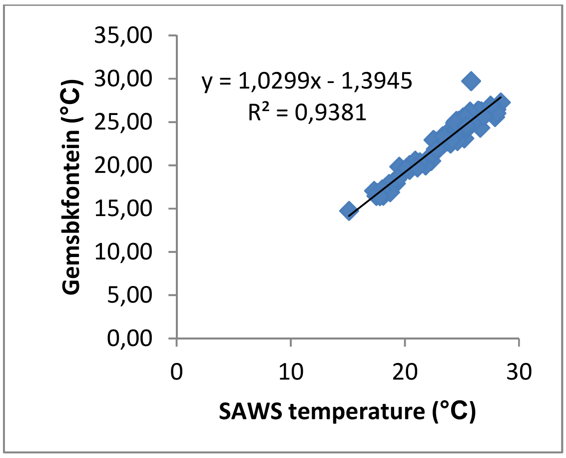
Station No.	Station Name	Y	X
	Arnot	-25.94444	29.79166
	Duvha	-25.95954	29.34094
	Hendrina	-26.03138	29.60135
	Kendal	-26.08805	28.96888
	Kriel	-26.25404	29.18008
	Matla	-26.28036	29.14229
0514467_A	BRONKHORSTSPRT:ROTSVA	-25.78333333	28.76666667
0516117_A	KANHYM-INVESTMENTS	-25.95	29.56666667
0516285_A	GEMSBOKFONTEIN	-25.75	29.66666667
0516285_W	GEMSBOKFONTEIN	-25.73333333	29.68333333
0477276_A	DELMAS SENSAKO	-26.1	28.66666667
0477309-AW	DELMAS WITKLIP	-26.15	28.68333333
0477368_A	DELMAS;PIONEER	-26.15	28.7
0479010_A	BETHAL:WILDEBEESFONTE	-26.16666667	29.51666667
0442046W	witbank W	-26.46	29.31
0515383W	Witbank Mag/Pow	-25.52	29.13
0515412W	Witbank Mun	-25.52	29.14
0515382AW	Witbank 1	-25.52	29.13
B2H004	Ossp	-25.92461	28.58588
B2H007	Koffiespruit	-25.99541	28.6635

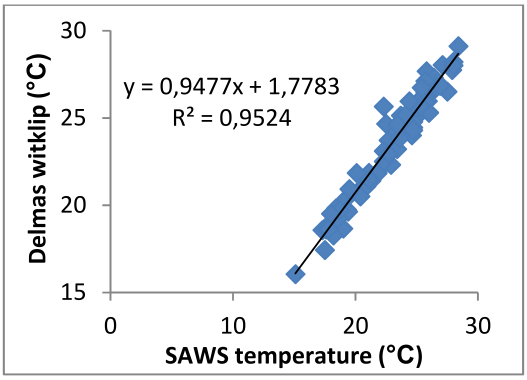
ANNEXURE B: RELATIONSHIP OF TEMPERATURE AT SAWS AND NEIGHBOURING STATIONS

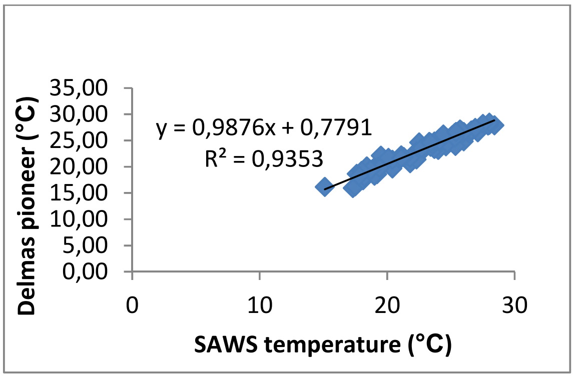

Bethalwildebeesfontein temperature (°C)
30,00
25,00
20,00
15,00
10,00
5,00
0,00
0
10
20
30
SAWS temperature (°C)
y = 0,9452x + 0,6095
R² = 0,9673


Bronkhorstpruit (°C)
35,00
30,00
25,00
20,00
15,00
10,00
5,00
0,00
0
10
20
30
SAWS temperature (°C)
y = 0,9765x + 1,8966
R² = 0,9592


Kanhym investments (°C)
30,00
25,00
20,00
15,00
10,00
5,00
0,00
0
10
20
30
SAWS temperature (°C)
y = 1,0077x - 0,4271
R² = 0,9584


Gemsbkfontein (°C)
35,00
30,00
25,00
20,00
15,00
10,00
5,00
0,00
0
10
20
30
SAWS temperature (°C)
y = 1,0299x - 1,3945
R² = 0,9381


Delmas witklip (°C)
30
25
20
15
0
10
20
30
SAWS temperature (°C)
y = 0,9477x + 1,7783
R² = 0,9524


Delmas pioneer (°C)
35,00
30,00
25,00
20,00
15,00
10,00
5,00
0,00
0
10
20
30
SAWS temperature (°C)
y = 0,9876x + 0,7791
R² = 0,9353

ANNEXURE C: RELATIONSHIP OF RAINFALL AT SAWS AND NEIGHBOURING STATIONS